D4.12: Update of Grid, urban and road infrastructure upgrading for meeting user expectations

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Technical References

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Acronym table

Acronym	Definition
AC/DC	Alternating current / Direct current
CCS	Combined charging system
CHAdeMO	DC charging standard for electric vehicles, enabling communication between the car and the charger
CP	Charging point
CS	Charging station (can have several CP)
DCFCS	Direct current fast charging station
DM	Demand management
DSO / TSO	Distribution system Operator / Transmission System Operator
DSS	Decision support system
D-STATCOM	Distribution Static Synchronous Compensator
DWPT	Dynamic wireless power transfer
EB	Energy Box
EMC	Electromagnetic Compatibility
EMS	Energy Management System
EV	Electric vehicle
ESS	Energy storage system
GO	Grid Operator
HV / MV / LV	High voltage / medium voltage / low voltage
IoT	Internet of things
PFC	Power Factor Corrector

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PV	Photo Voltaic power generation
PWM	Pulse width modulation
RES	Renewable energy source
SFC	Super-fast charger
SoC	State of charge
UC	Use case (of the INCIT-EV project)
V2B	Vehicle to building
V2G	Vehicle to grid
V2H	Vehicle to home
V2L	Vehicle to load
V2V	Vehicle to vehicle
V2X	Generic word for energy transfer from vehicle to other systems (building, home, other vehicle)

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0 EXECUTIVE SUMMARY

This report presents a summary of the activities of WP4 " Grid, urban and road infrastructure upgrading for meeting user expectations" of the INCIT-EV project. This work package lasted from January 2020 to December 2021. The objectives of this work package were to define the key aspects of the electricity grid and civil infrastructure for the demonstration of the INCIT-EV use cases and also for the future replication of the solutions. This is an update of D4.6.

WP4 is divided into five tasks:

- **Task 4.1 "Grid requirements for charging system deployment"**. The main objective of this task is to define the electric grid requirements to face a wide deployment of electric vehicles, with a focus on the project use cases.
- **Task 4.2 "grid services enabled by charging infrastructure and ESS deployment"**. The main purpose of this task is to establish synergies with the grid network by means of characterizing the grid services triggered by the penetration of electric vehicles in the grid thanks to services such as V2X. Furthermore, to propose complementary services to be demonstrated during the project, based on these principles.
- **Task 4.3 "Connection with DC networks and integration with tram / metro energy lines**". The objective of this task is to analyse and establish synergies with both DC electric and transport networks, especially with the tram and train lines thus exploiting new services triggered by these synergies. This will be possible thanks to the modelling and design of the general solutions which will be demonstrated on the demo-sites.
- **Task 4.4 " Infrastructure upgrading for dynamic wireless charging"**. This task has for purpose to adapt the road infrastructure in order to integrate underground wireless charging modules and to start setting the bases for the later design and deployment of INCIT-EV solutions, for urban and inter-urban applications.
- **Task 4.5 "Theft-proof parking systems for two-wheelers"**. The objective of this task is to define and model a theft-proof parking and charging system for electric two-wheelers (bikes and e-scooters), in order to obtain a reference solution to be later adapted to the particular specifications of the demo-sites.

This report summarises the main results obtained in these different tasks. A more detailed presentation of the results of each task of WP4 can be found in the final deliverables of each of these tasks of INCIT-EV : D 4.7, D 4.8, D 4.9, D 4.10 and D 4.11.

The delivery of this deliverable is done in accordance to the description in the Grant Agreement Annex 1 Part A with 6 month delay but no content deviation from the original planning.

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1 INTRODUCTION

1.1 Objectives of the report

This report presents a summary of the activities of WP4 " Grid, urban and road infrastructure upgrading for meeting user expectations" of the INCIT-EV project, which were carried out during the two first years of the project, from January 2020 to December 2021. The objectives of this work package were to define the key aspects of the electricity grid and civil infrastructure for the smooth demonstration of the INCIT-EV use cases and to address the updates needed for the future replication of the solutions.

WP4 is divided into five tasks:

- Task 4.1 "Grid requirements for charging system deployment". The main objective of this task is to define the electric grid requirements to face a wide deployment of electric vehicles, with a focus on the project use cases.
- Task 4.2 "grid services enabled by charging infrastructure and ESS deployment". The main purpose of this task is to establish synergies with the grid network by means of characterizing the grid services triggered by the penetration of electric vehicles in the grid thanks to services such as V2X. Furthermore, to propose complementary services to be demonstrated during the project, based on these principles.
- Task 4.3 "Connection with DC networks and integration with tram / metro energy lines". The objective of this task is to analyse and establish synergies with both DC electric and transport networks, especially with the tram and train lines thus exploiting new services triggered by these synergies.
- Task 4.4 " Infrastructure upgrading for dynamic wireless charging". This task has for purpose to adapt the road infrastructure in order to integrate underground wireless charging modules and to start setting the bases for the later design and deployment of INCIT-EV solutions, for urban and inter-urban applications.
- Task 4.5 "Theft-proof parking systems for two-wheelers". The objective of this task is to define and model a theft-proof parking and charging system for electric two-wheelers (bikes and e-scooters), in order to obtain a reference solution to be later adapted to the particular specifications of the demo-sites.

This report presents an overview of the main results of these different tasks.

1.2 Relation with other work packages and tasks of the project

WP4 has strong links with WP3 "User-centric EV charging solutions", which is in charge of the development of the different electric charging systems that will be demonstrated in INCIT-EV, including static conductive charging systems, and static and dynamic wireless charging systems.

WP4 has also strong connections with WP7 and WP8, which are in charge of the development of the different charging demonstrators. WP4 is in charge of defining and modelling solutions, which will be implemented in the demonstrators built in WP7 (Use Case 2) and WP8 (Use case 3).

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2 GRID REQUIREMENTS FOR INTEGRATION OF CHARGING SYSTEMS FOR ELECTRIC VEHICLES

2.1 Introduction

This section concerns task 4.1, which partners are CIRCE, Univ Eiffel, ENEDIS, Polito, EESTI, UL and ATOS. The main objective of task 4.1, has been analysing the most important grid requirements to face a wide deployment of electric vehicles with special focus on the project use cases. To achieve this objective, the work included two main parts:

1. A theoretical analysis of the technological and practical requirements that a large spread of EVs implies for the electric grid
2. An analysis of the impact that chargers to be developed and tested throughout the project could have on the electrical grid.

In the first part, the negative effect that a wide spread of electric vehicles charging facilities could have on the electric grid and the most common techniques to reduce this impact have been analysed. The negative effect has been treated in terms of load and voltage and power quality issues. The main standards that regulate these negative effects of the electric vehicle have also been analysed.

The theoretical analysis of the most common and recommended methods to reduce the impact on the grid that electric vehicle recharge may have has focused on: use of "grid friendly" power topologies in chargers, demand management and distributed generation and storage systems.

To complement the minimum requirements for a wide spread of electric vehicles without threatening the current electrical system, other aspects such as electrical safety, cybersecurity, communications interfaces and safety for dynamic inductive charging have been analysed.

For the grid impact analysis of the chargers, the different project UCs have been considered. They have been grouped in four frameworks:

- Urban framework: where UC2 (France, Dynamic wireless charging lane in urban area), UC6 (Spain, Low power DC bidirectional charging infrastructure for EV, including two-wheelers) andUC7 (Spain, Opportunity wireless charging for taxi queue lanes in airports/central stations) have been analysed.
- Peri-Urban framework: UC5 (Estonia, Tallinn peri-urban area-Estonia).
- Inter-Urban framework: UC3 (France, Dynamic Wireless Charging for long distance -prototype e-road).
- Parking framework: UC4 (Turin, Charging hub in a park-&-ride facility).

Effects that the charging devices to be developed in the project could have on the grid have been analysed using computer simulation tools. This work has been done in five steps:

1. Choice of representative electrical networks for the analysed use cases (since there were no real data on these).
2. Estimation of the use of EV charging stations.
3. Selection of the scenarios to be evaluated.
4. Simulation development and analysis of the effects of the chargers on the grid.

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5. Evaluation of main techniques to reduce the EV charge impact on the grid.

2.2 Electric vehicle charging impacts on the grid

Different possible effects of EV charging on the electric grid have been identified : EV charging stations act as additional stochastic loads in the distribution grid, which can be characterized by the following impacts:

- Active power demand and - for V2G and battery buffered installations - active power injection into the grid. With unallocated charging time slots, the grid nodes and paths can be easily overloaded, which can result in:
    - tripping of protection apparatus.
    - voltage drop in cables.
    - accelerated aging of power transformers.
    - frequency fluctuations in small isolated frequency clusters.
- Reactive power demand – the EV charging devices are designed to draw near zero reactive power from the grid. In some cases, if enabled by the EV charger internal topology, an EV charger can act as a static reactive compensator to mitigate upstream voltage problems.
- Electromagnetic compatibility – the power electronic devices convert electricity by pulse width modulation (PWM) control. With poorly designed filters, the modulation frequency may radiate back into the grid and into surrounding environment, causing malfunction of sensitive apparatus.

Different solutions for mitigating these impacts have also been identified :

- grid friendly power electronics topologies, which consists in designing the power electronics to assist the grid in reducing frequency harmonics, voltage and frequency balances.
- distributed generation and distributed generation + storage : this means to add to the grid additional energy sources, based on renewable energy sources (RES) and storage units to manage peak power demand constraints, smoothing the load charge, or even increasing the use of “idle” generation capacity during low demand hours.
- Demand management (DM), which refers to a set of actions designed to efficiently manage a grid's energy consumption with the aim of cutting the costs incurred for the supply of electrical energy. It should be noted that, using the Internet of Things (IoT), every grid device could potentially be connected to internet. This will help develop “smart” grids, and enhance demand management by allowing coordination between systems distributed across many consumers. Electric vehicles show both DM and IoT potential: when these vehicles are parked and connected to their chargers, their batteries can serve as aggregated energy storage capacity, which can be coordinated through an Internet connection.
- DM can also achieve great synergy with distributed generation, especially solar photovoltaic systems: when there are both generation and storage resources at the point of consumption, it is possible to optimize operation and reduce the total load on the power grid

2.3 Definition of charging scenarios

In order to simulate the effect of electric vehicle charging on the electric grid, different simulation scenarios have been defined, corresponding to the different use cases of the project :

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- Urban framework: where UC2 (France, Dynamic wireless charging lane in urban area), UC6 (Spain, Low power DC bidirectional charging infrastructure for EV, including two-wheelers), UC7 (Spain, Opportunity wireless charging for taxi queue lanes in airports/central stations) are analysed.
- Peri-Urban framework: UC5 (Estonia, Tallinn peri-urban area-Estonia).
- Inter-Urban framework: UC3 (France, Dynamic Wireless Charging for long distance -prototype e-road).
- Parking framework: UC4 (Turin, Charging hub in a park-&-ride facility).
- Overall Grid Framework: A mix from all previous Urban and peri-urban frameworks.

For each of these scenarios, a typical electric grid, corresponding to the context, has been defined. Typical electric vehicle power demand profiles have also been defined for each scenario.

2.4 Electric vehicle grid impact simulations

Using the scenarios described previously, simulations have been carried out with the objective of evaluating the impact of the charging points that are being developed in the project on the previously defined electric grids. Specifically, the impact on the network in terms of congestion of lines and / or transformers has been evaluated, as well as its effect on the distribution of voltages, over and under voltages. In addition to evaluating its possible negative effects, the influence of the most suitable EV load impact reduction techniques for each simulation scenario has also been evaluated. The obtained results are summarised in the sections below.

2.4.1 Urban framework

Due to their similarities, use cases 2, 6 and 7 were evaluated on the same network and with the same objectives but with different daily use profiles. Due to the lack of information about the network in which the charging stations will be located, it has been decided to use the IEEE benchmark low-voltage grid for Europe

This section presents results of a series of simulations to evaluate the EV charging impact on the grid in terms of losses, congestions and voltage problems of use cases 2, 6 and 7 and of the chargers that will be installed in each use case. These results are presented on figures 1,2 and 3.

As it can be seen, by including the charging stations of these use cases, the losses related to electric energy distribution are slightly increased compared to the base case (without any charger) taken as a reference (figure1). The different losses observed in each use case are related to the energy provided by the charging stations to the electric vehicles rather than to the power of the chargers, two 60 kW chargers in UC 2 and 50 kW in UC6 and UC7.

The connection of these chargers in the benchmark network, directly to the LV output of the transformer, without sharing connection with other loads, causes a low impact on the voltage profiles observed in the grid (Figure 2).

The installation of the charging stations near the secondary MV/LV substation and a correct sizing of the electric wiring does not generate any new congested sections, compared to the base scenario (Figure 3).

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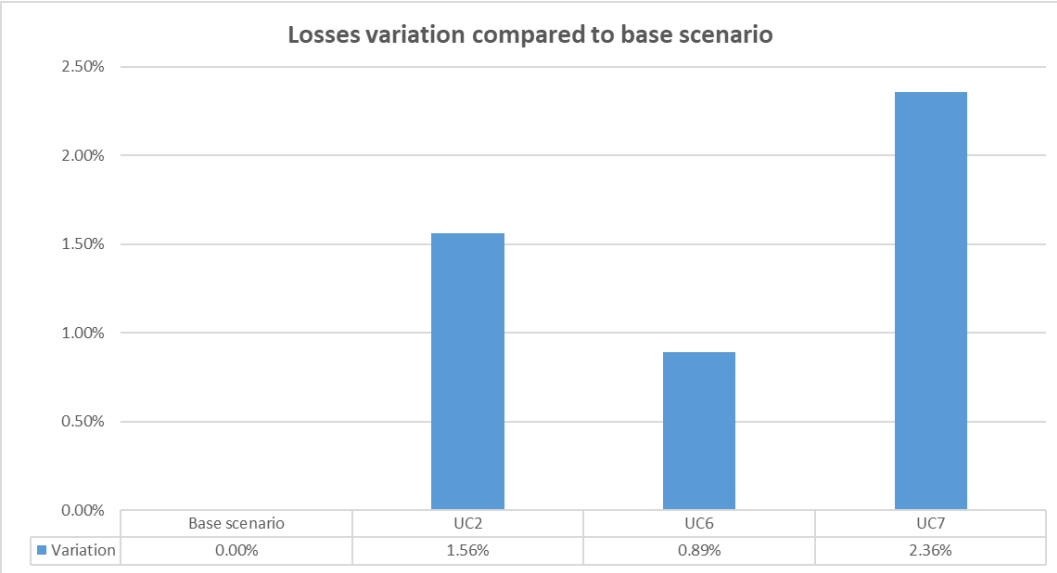

Figure 1. UC2, UC6 and UC7 grid impact in urban area (I), energy losses analysis.

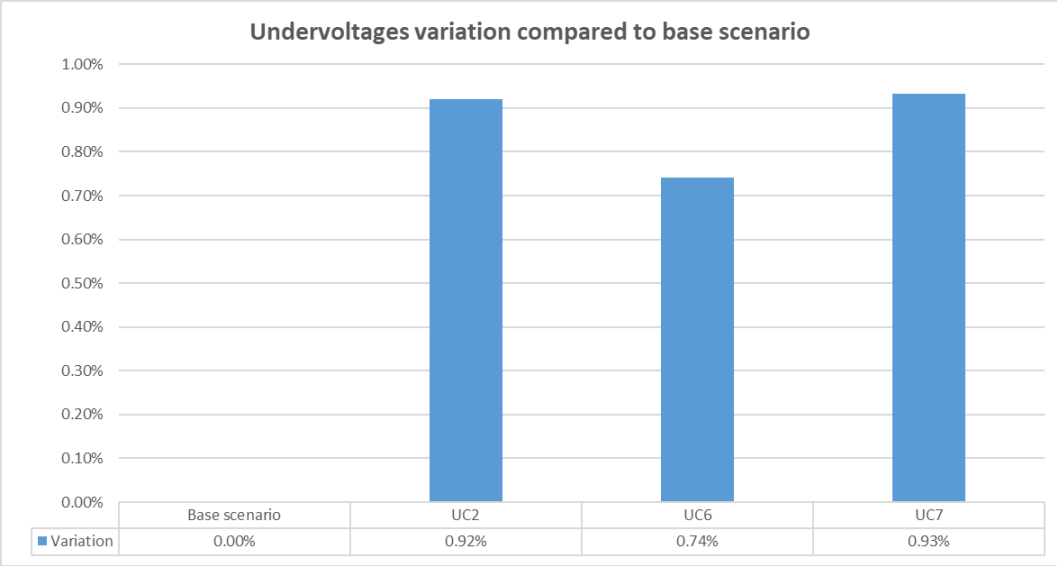

Figure 2. UC2, UC6 and UC7 grid impact in urban area (II), under voltages analysis.

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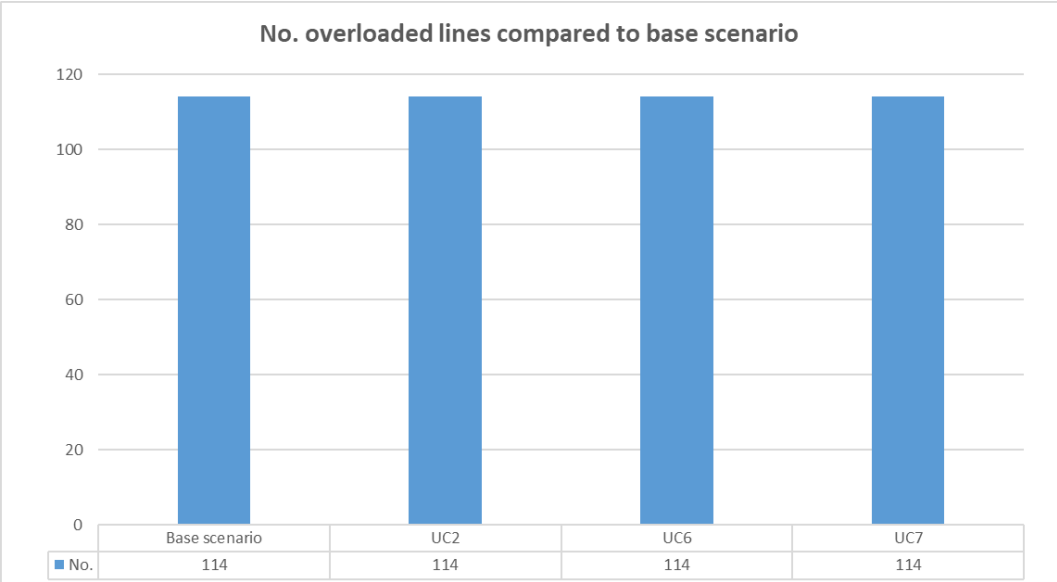

Figure 1. UC2, UC6 and UC7 grid impact in urban area (II), congestion/overloaded wire sections analysis.

As these three use cases will be located in urban areas, it was assumed that there will be no possibility of installing distributed generation or storage, so the only technique to reduce the EV grid impact is demand management. To evaluate the effect of this technique, a moment of the day with high energy demand has been chosen and several simulations have been made. For each use case, two scenarios of demand management of the electric vehicle charger have been analysed: (i) one in which the charger power is totally reduced (P = 0%) and the other (ii) in which it is reduced to half of the initial demand (P = 50%).

The simulations of demand management have shown that:

- The management of the demand for fast charging stations leads to a high reduction of the power supplied by the MV / LV secondary substation.
- Demand management has no influence on the voltage profiles, at least in the number of under voltages, in the area and at the time studied.
- Demand management reduces energy distribution losses.
- Finally, demand management also has no influence on the number of congested wire sections, since they are located in other areas of the studied network.

As has been observed, connecting the charging stations directly to the LV output of the secondary MV/LV substation makes any problem very local and does not affect other consumers. The negative impact related to losses can be solved with demand management, but this will limit EV charging capabilities. Due to the location of the charging stations, demand management has a limited effect. The impact in terms of congestion and / or undervoltage is avoided with a correct sizing of the connection and with the choice of a secondary MV/LV substation with sufficient hosting capacity for the charging station.

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2.4.2 Peri-urban framework

For use case 5, the impact of an electric vehicle charging station equipped with a super-fast charger (SFC) in an industrial / commercial area, such as those that can be found around European cities, has been evaluated. For these simulations, three possible locations of the charging station were taken into account, based on their geographical proximity to the substation that feeds the industrial area and five scenarios were tested:

- Base scenario. No charging station. This scenario is used as a reference for the other ones.
- Short distance scenario. The charging facilities are located near the HV/MV substation in an empty MV/LV secondary substation.
- Medium distance scenario. The charging facilities are located at a medium distance from the HV/MV substation in an empty MV/LV secondary substation.
- Large distance scenario. The charging facilities are located at a greater distance, in an empty MV/LV secondary substation.
- All charging stations scenario. 3 Charging stations are connected to the grid, in the 3 previous locations.

For the different scenarios, the grid impact was evaluated in terms of losses, congestions and undervoltage for a day. Besides the grid impact, two EV grid impact reduction techniques were evaluated for the medium distance scenario: distributed power generation and demand management. The results obtained are presented on figures 4, 5 and 6.

The installation of charging stations equipped with SFCs in the industrial zone increases the losses of energy distribution (see Figure 4). As expected, these losses increase with the distance between the point of consumption and the HV/MV substation. A substantial increase in losses is observed when including the three charging stations in the network.

It is also observed (see Figure 5) that the installation of SFC in the network increases the occurrence of under voltages. This phenomenon is especially important when 3 EV charging stations are installed in the area.

The simulations results also show that the installation of the new electric vehicle chargers increases the amount of congested or overloaded lines. When individual chargers are installed, up to 24 cable sections appear congested at least once a day (and sometimes more) at the charging facility itself or in the surroundings. When all 3 chargers are installed, up to 143 sections are overloaded (see figure 6).

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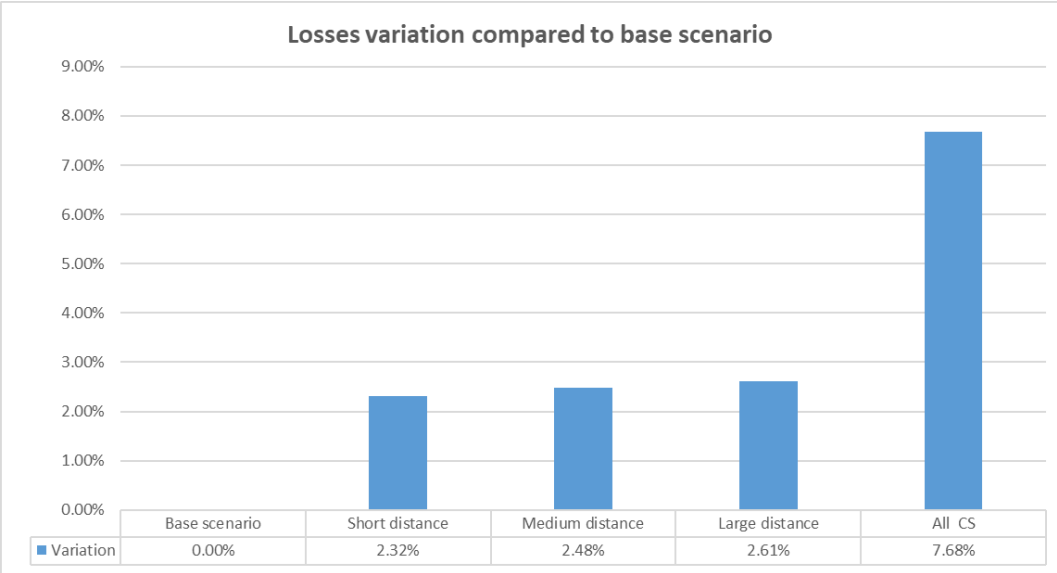

Figure 4. UC5 Charging station impact on the grid in peri-urban area (I), energy losses analysis

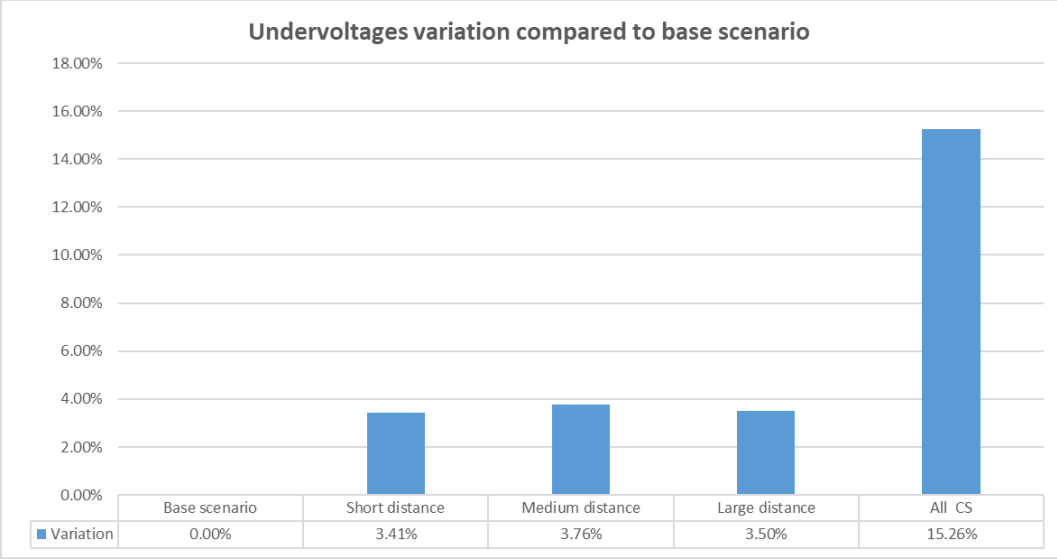

Figure 5. UC5 Charging station impact on the grid in peri-urban area (II), under voltages analysis.

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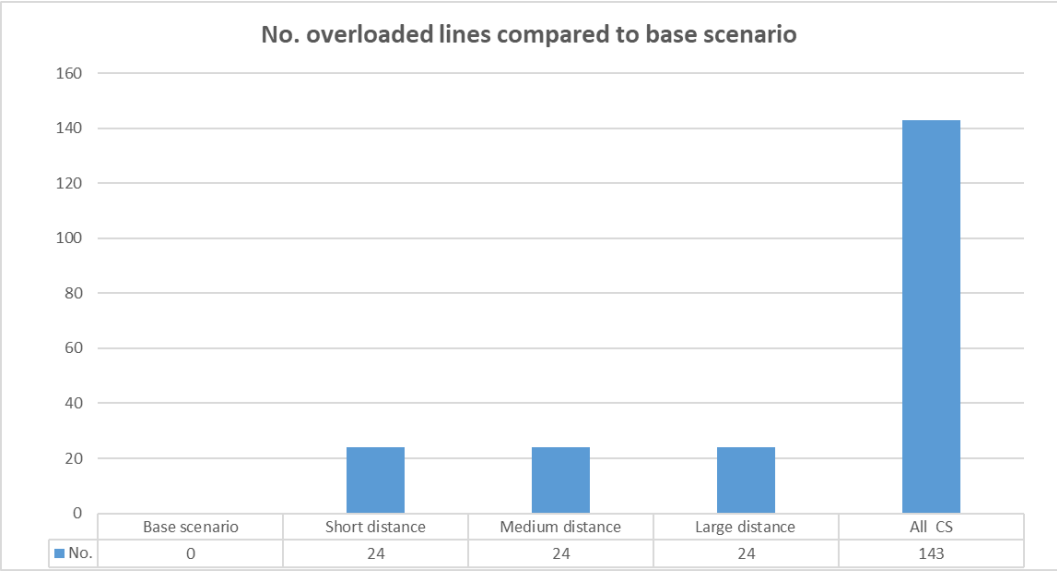

Figure 6. UC5 Charging station impact on the grid in peri-urban area (III), congestion/overloaded wire sections analysis

The simulations show that negative effects will be generated on the grid by the inclusion of SFC points. These negative effects are of course amplified when installing 3 charging stations, but the probability of installing several stations is low, due to the small size of the industrial/commercial area. Due to these negative aspects, the effect of using distributed generation and demand management to facilitate the integration of these chargers has been evaluated.

The first technique evaluated to reduce the impact on the grid of electric vehicle charging is distributed power generation. In this case, the installation of photovoltaic facilities of 100, 200, 300, 400, 500 and up to 600kW has been evaluated in the charger located at a medium distance from the substation of the area. The results of the simulations indicate that :

- The installation of a photovoltaic facility of up to 500 kW next to the charging station reduces losses with respect to the reference case. Above 500 kW, all the power produced is not consumed locally, which can generate losses associated with the transport of this energy. For this reason, the photovoltaic installation should be carefully sized.
- Adding photovoltaic generation also reduces the under voltages, whatever the power installed. However, an excessive power generation could cause the opposite effect and generate over voltages in the area.
- Finally distributed generation allows to reduce the number of congested wire sections along the grid.

Another solution to reduce the impact of SFC on the grid is demand management, which consists in stopping the charging if the grid is too congested. However, this reduces the advantage of using super fast charging, because the charging time would be increased. Therefore, demand management should be used for SFC only as an emergency option, in case of risk for the electrical grid to which it is connected.

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2.4.3 Inter-urban framework

The inter-urban framework represents an extrapolation of Use Case 3 to a 25 km long DWPT track with a maximal consumption of 33 MVA. As a consequence of its higher loading, direct supply from HV network was assumed. Only some preliminary simulations were performed for this use case, since the actual data from the UC is not yet available.

It was assumed that the network supplies two charging stations, with maximal consumption of 33MVA each. Charging stations are supplied through dedicated transformers, installed into an existing HV/MV substation. Additionally, there is a residual load in each HV/MV substation, which represents a general substation demand. Charging station consumption daily profile was defined based on assumptions on traffic on the road, and its daily distribution

Simulations considered two scenarios:

- Base case: existing situation, prior to installation of DWPT charging systems.
- Two UC3 charging stations installed in the network .

Results of the simulations focussed on voltage and power flow deviations in the network, caused by the newly installed charging stations. The simulations indicated an increase of power demand, associated with the DWPT charging, with peaks around 8.00 AM and 5.00 P.M., which correspond to peak traffic hours. This resulted in some voltage drops, but they remained limited.

It was concluded that the implementation of such charging systems , with a high electric consumption, can affect the operating conditions of the supply network. However, the impact depends on the available capacity of the network…This impact was rather limited in the chosen scenarios, but could be more important with a higher number of installed charging stations.

2.4.4 Parking framework

These simulations concerned the impact of the EV charging on the UC4 grid in Turin. In this use case, the charging stations are supplied by a tramway power substation. To define the power available for the vehicle charging, the difference between the nominal power of the substation (2.2 MW), and the energy used by the tramway service was calculated.

The available power for vehicle charging is defined by the graph on figure 7. This available power is represented by the blue line on the figure (which corresponds to measurements on the substation), and is compared with the red dotted line, which represents the sum of the power of all the charging points (increased by a factor of safety). When the blue line is above the red line, it means that sufficient power is available for the charging stations. On the contrary, when the blue line is below the red line, it indicates a possible overload of the network. This analysis indicated that the potential overload time is very small, representing only about 0.0072 % of the measurement period. These results validated the possibility to use the sub-station as power source for the UC4 demonstrator.

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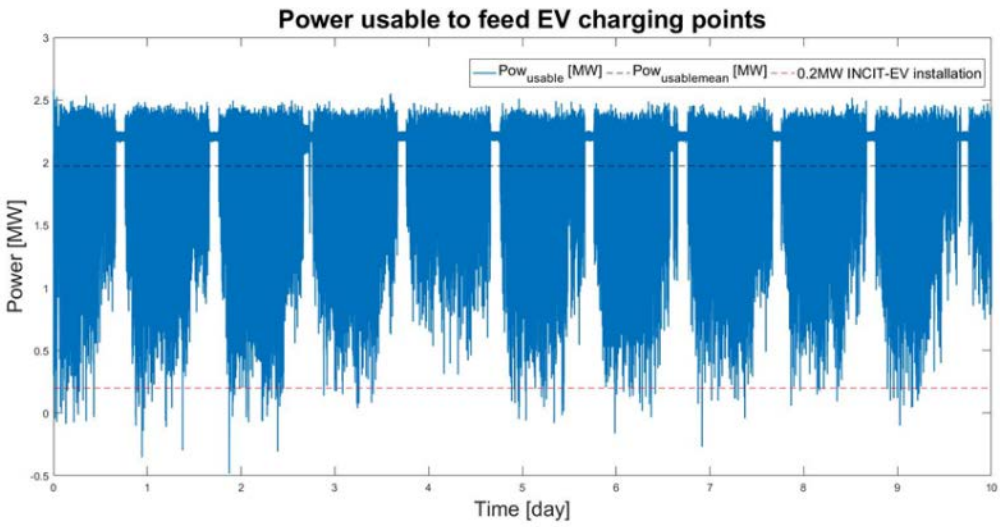

Figure 7. Power available to feed the EV charging points in UC 4 (measurements over a period of 10 days).

2.4.5 Overall grid framework

In this last part, several simulations scenarios have been defined, including photovoltaic, storage, demand management or V2G technologies to reduce the grid impact of the EVs or even provide support to the TSO/DSO in the operation of the grid.

The simulations have been divided in two different parts, one being local impact in the grid, where overloaded lines and voltage problems are analysed, and global impact in the grid, where frequency regulation analysis using V2G technology is analysed in different scenarios.

2.4.5.1 Local overloaded lines and voltage variation analysis

For this analysis, a large number of simulations has been carried out considering introduction of photovoltaic generation, battery storage and demand management.

For photovoltaic (PV) generation, 3 solutions have been considered :

- 10 kW PV facility installed exclusively in LV grids.
- 10 kW PV generation installed in LV and MV grids to study changes in grid losses mainly, as MV grids do not have overloaded lines or voltage problems.
- 30 kW oversized PV generation installed only in LV grids

For battery storage, scenarios where the battery charges for 12 hours (during night), and discharges for 12 hours (during day) , both at maximum power, have been considered. And in both cases, two battery powers, 7.5 kW and 30 kW (oversized) have been considered.

For demand management, 3 levels of charging demand reduction, 10%, 25% and 50%have been considered. This means either the EVs will leave the CS with a lower SoC than desired or that the charging process will be longer.

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Combined solutions, where two or three of the technologies are combined were also tested. Photovoltaic and battery storage are two technologies that are usually combined. With that combination it is possible to use the energy generated during central hours of the day, where the sun radiation is higher, in later hours of the day where the energy demand from the CS is higher. Simulations were carried out for 10 kW photovoltaic generation and 10 kW battery storage, and 20 kW photovoltaic generation and 20kW batteries (oversized case).

The objective of the different simulations was to analyse power losses, number of overloaded lines, and voltage variations. Each solution was first evaluated separately, and then the solutions were combined. It is not possible here to present all the results, and only the best results obtained with different (single or combned) technologies are presented.

Power losses

A comparison of the best power loss reductions obtained with different (single or combined) technologies is shown on figure 8. The figure shows that :

- Demand management is the solution which leads to the lowest reduction of losses.
- Combined PV and storage lead, logically to the best reduction, especially when their capacity is oversized.
- PV generation and storage alone give intermediate results. Storage has a higher reduction in losses, mainly because with storage it is possible to uses the energy when the peak demand occurs, whereas with PV only it is not possible to control the energy generated.

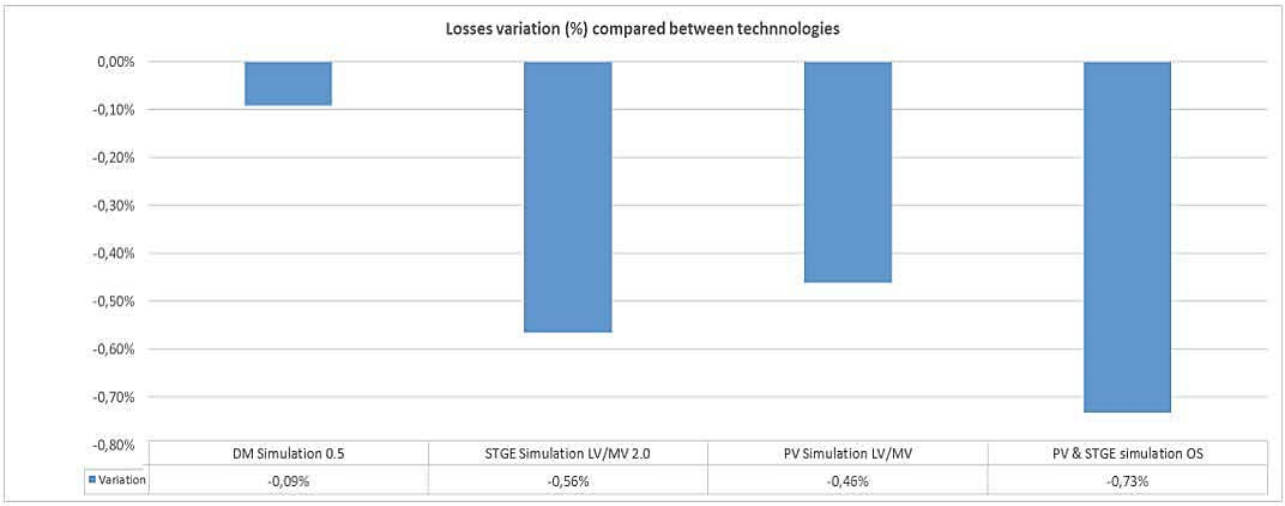

Figure 8 : comparison of losses variation (in %) between different scenarios,

The simulations of power losses have also shown that when using PV only, it is more efficient when it is installed in HV grids, because the power can be better distributeds. When a high PV power is installed in LV grids, it can lead to increased power losses, because PV generates more power during the central hours of the day, which cannot always be used optimally. Better performance is obtained by combining PV and battery storage.

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Overloaded lines

This evaluation has been conducted in terms of increase in percent of the number of overloaded lines, when using PV generation, battery storage, or demand management (each alone or combined), in comparison with scenarios without these measures. The simulations have shown that :

- Demand management (which means reducing the power consumption) is very efficient for reducing the number of overloaded lines.
- PV generation or battery storage alone are efficient to reduce the number of overloaded lines when they are correctly sized. However, when they are oversized (too much power generation), the effect can be opposite, and they can increase network overloading.

Figure 9 illustrates the best solutions for reducing the number of overloaded lines, using one single solution, or combined solutions. As for power losses, the combination of oversized PV generation and battery storage leads to the most efficient reduction of the number of overloaded lines.

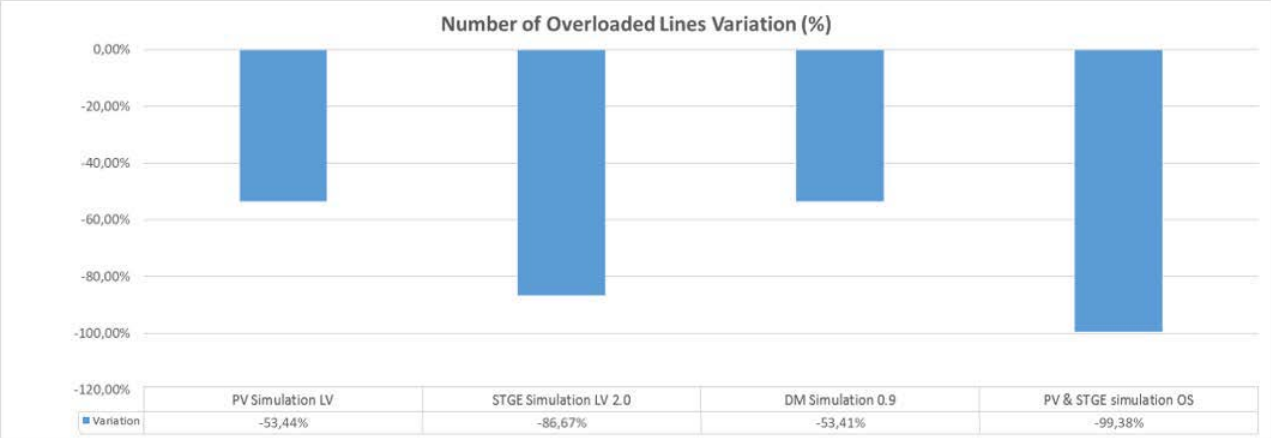

Figure 9 : comparison of reduction of number of overloaded lines (in %) between different scenarios,

Voltage variations

These simulations have been analysed in terms of number of undervoltages and overvoltages generated in the grid, which correspond to cases where the voltage variations exceed 10 % compared to the nominal value. Again, figure 10 illustrates the most efficient solutions for reducing under voltages, and figure 11 shows the associated overvoltages which can be generated. The figure shows that :

- storage, demand management (25 % power reduction) and combined technologies can eliminate almost totally undervoltages.
- only storage and demand management are able to achieve this reduction without raising the number of overvoltages. When PV generation is added, overvoltages occur. Between these two (storage and demand management), the first solution leads to the greatest reduction in undervoltages and also avoids reducing the energy provided to the EVs, thus leading to the best state of charge.

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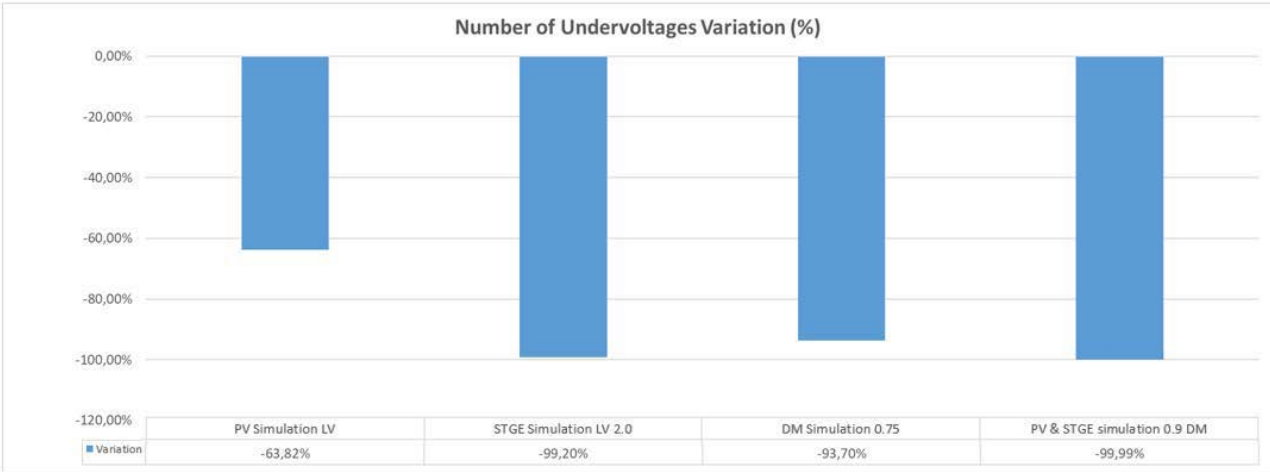

Figure 10 : comparison of the variation of the number of undervoltages (in %), for different scenarios.

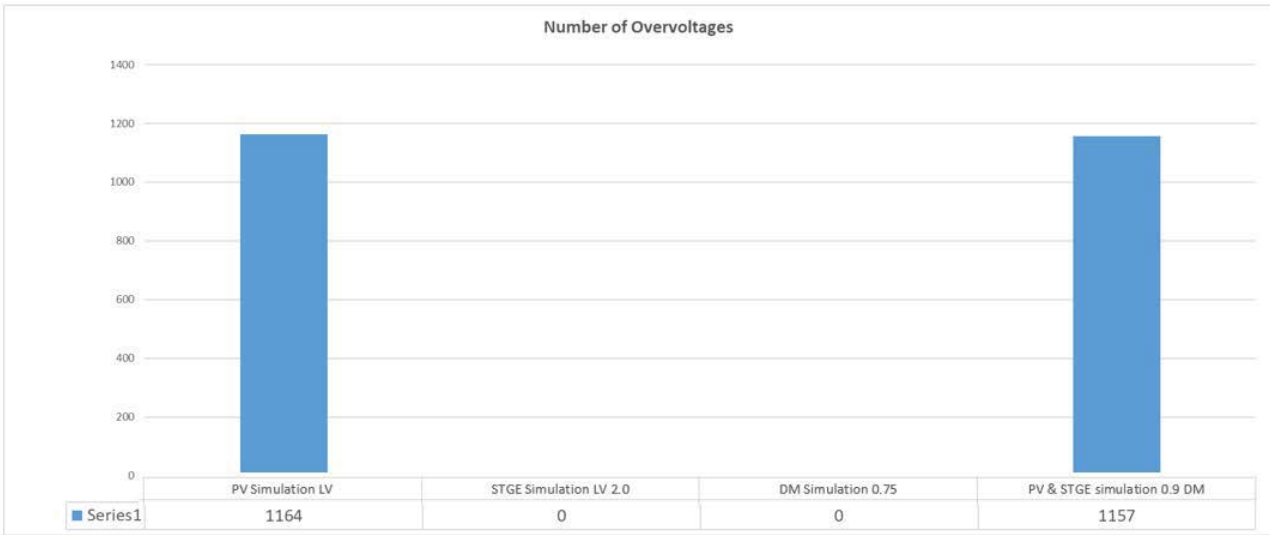

Figure 11: comparison of the number of overvoltages generated, for different scenarios.

2.4.5.2 Global performance

If a general comparison of the performance of different grid impact reduction techniques is made, it can be concluded that :

- demand management is the best grid impact reduction technique. This makes sense, as if the added load of the CS is the source of the problems, a reduction of this load means a reduction in the problems. But if those results are analyzed from the user's point of view, a power reduction of 25% in the peak charge load could mean a reduction in the final SOC of up to a 25%, when the EV is charging at peak demand with fast charging. This is the worst-case scenario for the user, as a 25% reduction in peak power most of the time does not mean a 25% energy reduction. Therefore, the

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reduction in the final state of charge may be lower (15 to 20%) but this can still be inacceptable for some users, who need a full battery charge.

- If both efficiency of the impact reduction and user demand are considered, battery storage or all combined technologies (PV + Storage + 10 % demand reduction) could be the best option, as a 10% reduction in peak power should not suppose a great reduction in the final SOC and problems still are greatly reduced. With really optimized PV generation and battery storage, demand management could be necessary only in exceptional cases.

2.4.5.3 Global frequency regulation analysis

Additional simulations have been made to study the capability of EV charging stations to provide frequency support to the power grid. The EV charging stations were represented as a PWM and a battery with its control. The frequency limits considered in these simulations are 50.02 Hz and 49.98 Hz, because with these limits EV chargers provide grid support and its effect can be evaluated.

The study has been made for different scenarios, dividing them if the EVs are already charged or if they are charging when the frequency event occurs. Most of the study cases have been carried out considering an underfrequency event in the grid. However, some overfrequency cases are also analysed.

The following scenarios have been considered, with implementation of the charging stations in the Low voltage grid (LV), medium voltage grid (MV); or high voltage grid (HV), and with a power demand for charging corresponding to 20, 40 or 60 % of the available power :

<u>Underfrequency event. EVs already charged:</u>

- Scenario 1: 60% LV + 40% MV ; 3 Study Cases: 20%, 40% and 60% Power

- Scenario 2: 40% LV + 60% MV ; 3 Study Cases: 20%, 40% and 60% Power

- Scenario 3: 100 % HV ; 3 Study Cases: 20%, 40% and 60% Power

- Scenario 4: 33% LV + 33% MV + 33% HV ; 3 Study Cases: 20%, 40% and 60% Power

o 4 Study Cases: Scenario 1, 2, 3 and 4 with 10 MW Power

o 4 Study Cases: Scenario 1, 2, 3 and 4 with 20 MW Power

<u>Underfrequency event. EVs charging:</u>

- Scenario 1: 60% LV + 40% MV ; 3 Study Case: 20%, 40% and 60% Power. EVs without frequency control

- Scenario 1: 60% LV + 40% MV: 3 Study Case: 20%, 40% and 60% Power. EVs with frequency control

<u>Overfrequency event. EVs already charged:</u>

- 10 MW Power in all scenarios; 4 Study Cases: Scenario 1, 2, 3 and 4 with 10 MW Power

The results of these different frequency simulations, with different scenarios, have led to the following conclusions :

Firstly, if the increment of frequency tries to be corrected by only disconnecting the EV chargers, it does not have a great effect, since the frequency is slightly corrected. Therefore, to correct the underfrequency or

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overfrequency error, the EV charging stations must have frequency control. Also, if a frequency event occurs while the EVs are charging, the EVs can stop charging and start correcting the frequency error without problem. However, the error correction may be delayed a bit because the primary frequency control is very weak. The frequency error is corrected when the secondary control comes in.

As a general conclusion from underfrequency simulations, the higher the number of EVs installed, the higher the active power supply to the grid, which leads to higher frequency error correction. A higher number of EVs also results in a higher active power loss to the grid. It has also been shown that Scenarios 1 and 3 present the best results in terms of frequency error correction. This is since, at high voltage, the EVs charging stations are close to where the frequency event occurs. In low voltage, the EVs charging stations are close to the consumers and feed them directly. Therefore, in both cases, it is not necessary to transport the power long distances along the electric grid, which leads to lower power losses and a better frequency correction. In scenario 2, as the predominant voltage is MV, there are more losses in power transport. Finally, Scenario 4 has less impact on the error correction because the new penetration is more distributed along the electric grid.

Concerning overfrequency event simulations, Scenario 1 has most of the absorption in the low voltage grid. Thus, power must be transported further through the grid, leading to higher losses. So, taking into account the losses in the power transport and the EVs power absorption, placing the EV charging stations at low voltage is the best solution for overfrequency cases. The worst case is Scenario 4 because the new absorption is more distributed in the electric grid.

Regarding the overloading of the lines, when all new penetration/absorption is on high voltage or is distributed throughout the network, there is no problem with the lines. However, when the penetration/absorption of power is important in low and medium voltage, there may be some cases of overloaded lines because the line is not prepared to withstand such much current. Therefore, in this case, a new study of the cables should be necessary to avoid overloaded lines.

2.5 Conclusion of task 4.1

The main objective of task 4.1 was to analyse the grid requirements to face a wide deployment of electric vehicles with a focus on the project use cases. To achieve this objective, project partners have analysed the technological and practical requirements that a large spread of EVs implies at a theoretical level, and then the impact that chargers to be developed and tested throughout the project could have on the electrical network.

The review on “Electric vehicle grid impact”, has pointed the negative effect that a wide spread of electric vehicle could have in terms of load, voltage and power quality. Following this direction, the standards that regulate these negative effects of the electric vehicle have been reviewed: the EN 50160 standard for medium and low voltage grids and the most common limits for high voltage networks operation have been analysed. In relation to the power quality requirements, the standards that regulate these aspects have also been analysed.

To complement the minimum requirements for a wide spread of electric vehicles without jeopardizing the current electrical system, other aspects such as electrical safety, cybersecurity, communications interfaces and safety for dynamic inductive charging have been analysed in task 4.1.

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This theoretical analysis has been completed by a study of the most common and recommended methods to reduce the impact on the grid that electric vehicle recharge may have : use of "grid friendly" power topologies in chargers, demand management and distributed generation and storage systems. This analysis has also shown how these techniques are addressed in several of the project's use cases.

In addition to the previously described theoretical work, the effect that the chargers to be developed in the project on the grid have been analysed using computer simulation tools. This work has been done in different phases : (i) choice of representative electrical networks for the analysed use cases (since there were no real data on these); (ii) estimation of the use of EV charging stations; (iii) choice of the scenarios to evaluate; (iv) development of simulations and analysis of the effect of the chargers on the grid; (v) finally, some techniques have been evaluated to reduce the EV charge impact on the grid.

Simulations work has been focused on a wide deployment of EV charging stations along LV, MV and HV grids, and their effect on grids in terms of energy losses, overloaded lines and voltage deviations and their effect on supporting grid operators in frequency regulation.

Simulations of PV power generation have shown that when PV facilities are implemented with a proper power, installed exclusively in LV grid and in both LV and MV grids, a reduction in losses is obtained, this reduction being higher when the PVs are installed in the whole grid. On the contrary, when oversized PVs are installed, new problems appear as the grid must manage a higher power generation in the central hours of the day, when demand is not at its highest level. Because of this oversized generation, power losses may increase.

Simulations of effects of battery storage have shown that when it is oversized, there is still a reduction in losses, but this reduction is lower than with correctly sized batteries (it is important to remember the full power charge and discharge cycles of the battery). As the battery does not generate energy but stores energy coming from the general grid and its profile is adapted to the EV demand, there is no increase in losses as we see with PV simulations, where energy is generated in central hours of the day where there is no peak in demand.

The simulations have also shown that with a higher penetration of EVs, the number of undervoltages increases. As these undervoltages are only in LV grids, the increase is not proportional to the increase in penetration, in fact, in scenarios 2 and 4 there is no increase between 40 and 60% penetration. If this increase in penetration would have been proportional in all grids, LV grids would not have been able to bear this increase.

When PV is implemented in all the CS spread out through the grid, overvoltages increase a lot. Even if a reduction in losses is achieved, installing PV generation without a proper study of its impact can create worse problems than the reduction in losses achieved.

These overvoltage increases add up to the ones indicated in the overloaded lines section, where a correctly sized PV implementation reduced grid impact, but oversized PV or excessive PV generation not only does not reduce impact in the grid but increases it.

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Finally, the greatest reduction of undervoltages can be achieved by storage, demand management and combined technologies, but only storage and demand management are able to achieve this reduction without raising the number of overvoltages.

If a deeper study of storage and PV is done and both are properly sized and, in the case of batteries, the usage profile is better adapted to PV generation and CS demand, most of the problems could be solved leaving the demand management technology for exceptional cases where demand is higher than expected and where PV and battery are not able to solve all grid problems.

As a conclusion of the frequency regulation analysis, the EV charging stations must have frequency control to correct underfrequency or overfrequency errors. Also, if a frequency event occurs while the EVs are charging, the EVs can stop charging and start frequency correction with a small delay. As a general conclusion from underfrequency simulations, the higher the number of EVs installed, the higher the active power supply to the grid, which leads to better frequency error correction. A higher number of EVs also results in a higher active power loss to the grid. At high and low voltage, it is not necessary to transport the power long distances along the electric grid. This is since, at high voltage, the EVs charging stations are close to where the frequency event occurs. In low voltage, the EV charging stations are close to the consumers and feed them directly. Therefore, the power losses are lower, and the frequency correction is higher. Moving to overfrequency event simulations, the most power absorption takes place in the low voltage grid, since power must be transported further through the grid (from where the frequency event occurs), leading to higher losses. So, taking into account the losses in the power transport and the EV power absorption, placing the EV charging stations at low voltage is the best solution for overfrequency cases. The worst case is when the power absorption is more distributed in the electric grid.

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3 GRID SERVICES ENABLED BY CHARGING INFRASTRUCTURE

3.1 Introduction

This section concerns task 4.2, which partners are Univ Eiffel, ENEDIS, CIRCE, REE, POLITO, MRA-E, PITP, EESTI, UL (IRI UL), and ATOS. The main objectives of task 4.2, which concerns grid services enabled by charging infrastructure, were:

- To perform a state of the art review related with potential grid services enabled by the charging infrastructure and electric vehicles.
- To define scenarios of use of the different grid services, related with the different types of use cases that will be developed in the project (urban, peri-urban, interurban, parking).
- To simulate the impacts of the different services on grid performance, for different use cases.

3.2 State of the art about grid services

The review has been divided in two parts : Services related with grid management and correction of grid problems, and V2X services, which concern the use of energy stored in vehicle batteries for other systems.

3.2.1 Services of assistance to the grid

Grid operators manage electricity supply and demand in the electric system by providing a range of grid services. Grid services are activities that grid operators (GO) perform to maintain system-wide balance and appropriately manage electricity transmission. Such services can include:

- Operating services: Scheduling and dispatch techniques. Because in most electrical systems energy storage is nearly zero, it is necessary to maintain a balance between power production (by generators) and power consumption (demand from consumers). For that, careful scheduling and dispatch are necessary. Scheduling refers to before-the-fact actions (for example scheduling a generator to produce a certain amount of power the next week), while dispatch refers to the real-time allocation of the available resources.
- Reactive power and voltage control: Reactive power is used to synchronize voltage and current. Modern inverters can both provide and absorb reactive power to help grids balance this important resource. Reactive power can be used to compensate voltage drops, but it must be generally provided closer to the loads than real power needs (this is because reactive power tends to flow badly through the grid). It should be noticed that voltage can also be controlled by using transformer coils and voltage regulators.
- Frequency control: this refers to the need of ensuring the grid frequency within a specific range around the nominal frequency. Mismatch between electricity generation and demand causes variations in frequency, so control services are required to bring the frequency back to its nominal value and ensure it does not vary out of range.

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- Asset Lifecycle Management Services: designed to help transmission and distribution operators to optimize their asset management strategy using digital technology to improve the monitoring, recording and analysis of grid operations and predict asset behaviour.
- Renewable generation: The grid integration of renewable generation simultaneously requires additional ancillary (*auxiliaries*) services and has the potential to provide ancillary services to the grid. The power converters (inverters, rectifiers, ...) that are installed with distributed generation systems and solar systems have the potential to provide many of the ancillary services that are traditionally provided by spinning (as a power reserve) generators and voltage regulators. These services include reactive power compensation, voltage regulation, and flicker control, active power filtering and harmonic cancellation.
- Electric vehicles: Plug-in electric vehicles have the potential to be utilized to provide auxiliary services to the grid, specifically load regulation and spinning (power) reserves. Plug-in electric vehicles can behave like distributed energy storage and have the potential to discharge power back to the grid through bidirectional flow, referred to as vehicle-to-grid (V2G). Plug-in electric vehicles can supply power at a fast rate which enables them to be used like spinning reserves and provide grid stability with the increased use of intermittent generation such as wind and solar. The technologies to utilize electric vehicles to provide ancillary services are not widely implemented today, but have a lot of potential [1].
- Automation and system protection (and: EMC immunity)
- Solutions for energy imbalances.

3.2.2 V2X services

The term V2X is used as a generic word that can describe several types of situations in which the energy, that is stored in the battery of a vehicle, is transferred *from* the vehicle to another system. The distinction between the different kinds of V2X use cases mainly resides in the characteristics of the targeted system.

When the vehicle is used to provide a service to the distribution or transportation network of electricity, we are in presence of “vehicle to grid” (V2G) technology. When it is used to provide a service to a large subsystem that is located downstream of the electricity public network (e.g. a building, a small factory, a micro-grid …), we are in presence of “vehicle to building” (V2B) technology. When the vehicle is used to provide a service to a residence, we are in presence of “vehicle to home” (V2H) technology. Lastly, when the vehicle is directly connected to a small electric equipment that is off the grid (e.g. a water pump, a mobile refrigerator …) we are in presence of “vehicle to load” (V2L) technology.

Vehicle to grid (V2G)

The V2G technology is the most known and discussed practice of bidirectional usage of the battery of electric vehicles. This term is sometimes even used as a generic way of talking about a vehicle discharging its battery into any system. Here, it concerns only the vehicle discharge into the distribution or transmission electricity network.

Different services can be provided to the network :

- Local active or reactive power flexibility, to relieve some topological local constraints on the low or medium voltage distribution networks.
- Frequency regulation. Network operators have interest in those services.
- Power flexibility on a larger scale, with interactions with electricity market actors.

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This technology requires advanced systems in the car, the charging point or/and in the network. It also requires telecommunication infrastructures (locally and on a large scale) where the signals and control data will transit.

Vehicle to building (V2B)

V2B is encountered when a vehicle or, most of the time, a group of vehicles is used to manage, optimize or support the energy consumption of a building or of a site (commercial, tertiary, industrial). The vehicles are located on the site on which the energy is needed. Contrary to V2G, the specificity of this technology is that it is transparent for the rest of the world (public network and electricity market actors). V2B can be achieved by installing smart energy management systems on the sites.

Vehicle to home (V2H)

Vehicle to Home is the second most known technology when talking about bidirectional charging. It is a smaller scale of the V2B already described, on a residential level. The energy management is simpler. The use cases associated to this technology can go from emergency supply of the house in case of a public network blackout to optimisation of the energy consumption of the house in situations with a local storage and production capacity.

Vehicle to Load (V2L)

V2L consists of a single electric vehicle providing energy to a load that is not connected to any larger network. This technology has not really been developed yet but has a strong economic potential. It can be used for emergency purposes (to supply a vital or useful device in the field, when electricity network is down) or for casual use when the use of an electric battery is seen as more convenient than another power source (fuel generator). The main advantage of this technology is that the vehicle can *travel* to the load that needs its energy. It can thus be really useful in remote places where the public electricity network is not dense (rural or poor areas).

Vehicle to vehicle (V2V)

This specific case of V2L is useful to help an electric vehicle that is too far away from a charging point or with an empty battery. Because of the inevitable losses, this situation probably does not have a real economic potential, besides the mentioned help scenario.

3.3 Definition of grid services scenarios

The grid services considered in the project and in the different use cases are various and numerous. In this sub-task, it was decided to focus on the grid services which are the more relevant for the inter-urban Use Case.

To maintain grid stability at any time, voltage and frequency levels should be controlled within pre-defined fixed limits. Voltage is generally affected by reactive power variation and is controlled by controlling the reactive power injected to the grid. Likewise, frequency is generally affected by the active power variation, and is controlled by controlling active power injected to the grid.

Many solutions are used to prevent voltage and frequency fluctuation. Energy storage systems (ESS) are widely used to overcome load oscillation. The energy is stored when supply exceeds demand and used when

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needed. ESS with fast dynamics (using power electronics converters) can resolve fast load oscillation caused for example by EV charging.

Controlled smart charging EVs can participate in load shifting, and then reducing power variation. It is known for EV users to charge their vehicle after returning home (between 18 and 20 PM). Smart charging enables EV charging when load exceeds demands (normally after midnight), which is also when peak power is passed and the energy bill is at the minimum. This applies to dynamic wireless charging EVs, where the users charge their vehicles on the road, going to or from work, before and after peak power demand.

D-STATCOM and other FACTS techniques are used as grid services to maintain voltage, frequency and power factor at needed levels. The STATCOM can be used for reactive power compensation, for voltage regulation, and for frequency regulation when equipped with ESS.

In the work of task 4.2, Energy storage deployment (ESS) has in particular been investigated. Grid energy storage is a set of methods used for energy storage on a large scale within an electrical power grid. Electrical energy is commonly stored during times when its generation has a tendency to overtake the demand, resulting in reduction of its prices (especially from intermittent power plants such as renewable electricity sources (RES) such as wind power, solar power, etc.), or when the demand is low, and later returned to the grid when the demand is high, and electricity prices tend to be higher.

Any electrical power grid must match electricity production to consumption, both of which vary drastically over time. Energy storage systems (ESS) are a valuable asset for the electrical grid. They can provide benefits and services such as load management, power quality, and uninterruptable power supply to increase the efficiency and supply security.

3.3.1 Scenarios definition on the vehicle side

Different scenarios where the EV could provide services to the grid will also be investigated, but the analysis is made from the EV side, having in mind the limitations and characteristics of the vehicle and the charger.

V2V Charging

V2V stands for "vehicle to vehicle" and refers to the exchange of energy between electric vehicles. This energy exchange process can be due to two reasons:

- Exchange of energy between vehicles in the event of an emergency due to lack of energy in a vehicle and lack of recharging infrastructure in the vicinity. This is still a developing technology.
- Exchange of energy between vehicles for proper management of vehicle fleets, or in moments of difficult or limited access to the electricity grid.

The energy exchange among vehicles for a proper management of fleets can be made in two ways, depending on the type of energy exchange:

- V2V in AC using the distribution grid as a reference. This design uses common V2G chargers connected through the AC distribution network; one vehicle provides energy to the system while the other charges its batteries.
- V2V in DC in the same EV charger. This configuration requires specific chargers with connectors and other infrastructure for at least two vehicles. The main advantages of this configuration are that (i)

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it is much more efficient as it avoids exchanging energy to alternating current and from alternating current and (ii) the distribution network is not necessary, so it could be done in isolated locations. This solution is going to be tested in UC6.

3.3.2 Grid support services – use of CIRCE Energy box

As has already been indicated throughout this document, the electric vehicle and the associated charging facilities can be providers of support services to the electricity grid in different ways:

- Through active or reactive power generation.
- Individually or coordinated with other charging facilities.
- Locally or in aggregation with other facilities for larger sets of the electrical system.
- Only to the electrical network (V2G) or as part of other installations or microgrids (V2B, V2H or V2L).

In any case, to provide these types of services, both the charger and the network to which it is going to provide the services must be properly monitored and managed.

Most of today's EV chargers have equipment to be monitored and controlled remotely by control centres, from operators of charging facilities or the DSO/TSO, in order to provide support services to the grid. This monitoring and control allows: commercial management of the charger (use, customer management, payments, etc ...), verification of its status, demand management (limitation of maximum power or duration of the charge for example) and provide services of grid (power limitation, reactive power management or, in some cases, discharge of energy to the network). These possibilities are limited when the charger is a part of a larger infrastructure (chargers of different types and manufacturers, distributed generation and / or storage facilities, etc ...) and it is necessary to manage all the systems in a coordinated way (within an electric station, a building, a house ...). The most common situation is that each provider has its own monitoring and management platform making the integration complicated. Therefore, CIRCE will test the Energy Box (EB) in the chargers it is developing for the use cases 6 and 7. EB is meant as a monitoring element, information concentrator, for communication with external agents, and for the operation of EV chargers in these UCs.

The CIRCE Energy Box is a multi-purpose concentrator for the operation of advanced electrical networks and Smart Grids. In addition to its versatile communication capabilities, it contains an embedded computer that provides computing and processing capacity to implement distributed computing: capture and storage of information, execution of algorithms and control of the installation, among others.

As it can be can seen, the EB is the cornerstone of CIRCE developments to provide services to the electric grid:

- Locally, in response to the information coming from the elements of the installation: demand management based on the overall consumption, compensation of the total installation reactive, reactive management to provide voltage support services, asset management to provide frequency services and management of all system elements (EV charger, distributed storage and generation, and other manageable consumption).
- Remotely, following instructions from a remote control centre, either from the management company of the chargers or from the DSO / TSO.

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3.3.3 GRID SERVICES IMPACT SIMULATIONS

Simulations have been performed to evaluate the impact of the different grid services listed previously on the grid. These simulations are based on the same electric grid description and charging station usage patterns as In task 4.1 (see section 2). They concern different frameworks : urban framework (for UC2, UC6 and UC7), inter-urban framework (UC3) and peri urban framework (UC5).

3.3.3.1 Urban framework :

The reference electric grid already used in task 4.1 for the Urban framework has also been used for simulating the impact of grid services. Several simulation have been made, to evaluate impacts of :

- Unbalanced charge of an EV
- Discharging the vehicle batteries to provide energy to the grid, (V2G)
- Charger reactive power control

As most of the consumers and equipment connected to low voltage grids are single-phase, these networks tend to operate unbalanced. It is for this reason that a charger that could operate unbalanced, could support the operation of LV networks. This effect has been evaluated and compared by moving this charger upstream, next to the MV / LV transformer, and downstream of the network, next to the most congested points with undervoltage problems.

V2G technologies could be a source of grid supporting services, as discussed in the state of the art. This possible service has been evaluated and compared by placing the charging upstream, next to the MV/LV transformer, and downstream, next to the most congested points with undervoltage problems.

Some electric vehicle chargers can regulate the reactive power that they exchange with the grid, which can be a very interesting grid service. The effect on the network of this possible service is evaluated by simulating the installation of an EV charger upstream in the grid and another downstream. The charger has been programmed in such a way that it regulates reactive power in order to keep the voltage of the furthest point of the grid within limits.

Details of the simulations can be found in deliverable D4.8 of INCIT-EV. To summarise the results, it has been shown that EV charging stations can provide grid services to LV grids but to have an important effect, the charging stations should be placed near the area with voltage or congestion issues (“downstream” simulations). On the other hand, locating high power chargers far away from the transformer can cause additional problems when charging vehicles at full power: additional congestions and under voltages. These problems would be higher if installing high power chargers downstream in LV grids or if the grids are long and/or weak.

3.3.3.2 Peri-Urban framework

To evaluate the local effect of the grid services that a Super Fast Charger (SFC) can provide, two operating options have been simulated: discharge of the electric vehicle batteries (V2G) and reactive power injection with no active power exchange. These two services have been compared to a “base scenario” in which the EV charger operates at nominal power in a minute in which the grid consumption is one of the highest of the day. The following results have been obtained :

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- Battery discharge and reactive power injection (without active power exchange) reduce losses and the energy provided by the HV/MV substation. In the V2G case, the phenomenon almost doubles since it not only stops consuming energy but also discharges energy to the grid.
- Both services have similar and good results avoiding under voltages.
- Both services avoid all the congestions.

3.3.3.3 Inter-urban framework

Simulations have been performed for the Versailles use case, with starting grid model as suggested in D4.7 for the inter urban situation. Since the exact grid specifications were not known, different static loads were connected to take into consideration a random distribution situation. The dynamic load considered describes the presence of 25 km of dynamic wireless charging lane, with 34 MW capacity. Since the simplified model considers a two charging station model, the maximum allowed power is 17 MW per station.

In the simulations, the use of a D-STATCOM (Distribution Static Synchronous Compensator, of 20 KV and +/- 3 MVAR) has been simulated, for voltage regulation, and reactive power compensation. Different regulation techniques have been tested, and a three level hysteresis control for the voltage (using reactive power) and frequency (using active power) has finally been selected.

The simulations have shown that the use of the D-Statcom can reduce voltage variations, and also compensate reactive power.

3.3.3.4 Parking framework

Because the Turin tramway grid is a DC unidirectional system, no V2G application is available in UC4. Because the substation power is very large, the charging stations pose no real threat to the functioning of the tramway lines that are active in the substations, even in the worst possible operating conditions (I.e. peak time, excessive accelerations and braking, new and more energy consuming trams with a/c on during summer etc.).

The simulations that were performed had for objective to evaluate the contribution of an electrochemical energy storage system, for peak shaving purposes during intense tramway traffic periods (for example commuter peak times in the morning and early evening).The simulation were carried out considering that the substations' nominal output of 2.2 MW can reach 3.3 MW for 1h and up to 4.4 MW for 1 min during critical conditions. Two possible loads, 200 kW and 500 kW, and a correspondingly dimensioned electrical storage system , were considered.

In Turin, the power consumption of the tramways was measured, to determine the power available for vehicle charging. Then, simulations were performed by adding the 200 kW or 500 kW charging hub to the energy consumption of the electric sub station . It was found that adding the charging hub would increase overload occurrences. In order to avoid this scenario, a storage system would be more than welcome.

For the 200 kW charging hub, the maximum power recorded is 681.65 kW more than the nominal capability of the SSE, and the storage system was sized for the maximum Δt in which the current consumption was greater than the nominal capacity. This lead to a storage capacity of 0.6817 kWh, in order to solve the aforementioned overload for 3.6 seconds

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For the 500 kW charging hub, in order to avoid overload, the storage system had to be sized for a 981.65 kW overload with a duration Δt of 5.9 s. The result is a 1.6088 kWh storage system capacity.

For the two cases, the required storage capacity is relatively small, and it was concluded that the best solution would be to use a supercapacitor, which is capable of delivering a high power in small time frames

3.4 Conclusions and perspectives of task 4.2

3.4.1 Benefits of Grid services

For France, The recent reports published in 2019, by both French DSO Enedis, and TSO RTE, show smooth and seemless integration of e-mobility at a minimum cost on both distribution grid and bulk system. This is due to well designed networks (to cope with electric heating in winter) and to the tariffs (peak / off peak) which have been used for decades in France. However, more advanced smart charging and V2X might play a further role in reducing integration costs and extracting best value from the future EV usage through its storage capacity.

Energy bill reduction

Currently, the simple charge shifting at off-peak times can enable electric vehicle owners to make significant savings, compared to a "natural", unmanaged charge. Depending on user profile and type of EV consumption, additional savings could be made through avoided power capacity increase cost, and self consumption charging optimisation.

Smart charging (V1G) levers

Smart charging can be driven by three means of optimisation:

- adjusting the charging power (power management) to reduce the vehicle's power demand, thus avoiding to increase subscribed power of the premises;
- time-shifting the charging process (time of use management) incentivised by price offers from suppliers;
- maximising self-consumption, with solar production surplus during the day rather than charging in the evening ...

Future Bi-directional Smart charging (V2X)

Bi-directional smart charging allows power flow to circulate in both directions: from the grid to the car but also from the car back to the grid, when power injection is needed. The principle of Vehicle-to-Home (V2H), Vehicle-to-Building (V2B), and Vehicle-to-Grid (V2G) consists of reinjecting the electricity contained in the battery into the household or building's private grid or the public electricity distribution network, respectively. These technologies could offer further flexibility to the grid (for bulk system at national level or distribution grid at local level) and might be called through specific B2C – B2B contracts.

The highest value of V2G has been assessed for frequency system participation and the amount for the French system (Analysis by RTE) ranges between 100 € - 900 € per car, depending on competition environment with other vehicles or storage devices.

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3.4.2 Conclusions

In task 4.2, a state of the art was first performed, about the potential services which could be available with the grid and notably in terms of assistance to the grid, including in particular V2X techniques. Then, the task focused on specific grid services, which are frequency and voltage regulations, and defined several grid scenarios to consider, in relation with the INCIT-EV use cases, before designing technical solutions for these services. The proposed solutions are based on an ESS integration in the electrical architecture.

Simulations were then carried out by the different partners, for the different scenarios, in order to analyse the performance of the grid services and also their impact on the electrical network. Regarding services to the grid, voltage and frequency regulation, and reactive power compensation have been tested by simulation. Reactive power compensation is assured by injecting reactive power into the grid. The simulation showed that the amount of injected (or absorbed) reactive power can be controlled to maintain unity power factor, or to control the voltage level to ensure voltage stability. Those two services do not need the addition of a battery storage system, and then can be achieved easily.

Frequency regulation requires injecting (or absorbing) active power from the grid to maintain frequency level. This control method can contribute to frequency regulation, and to the charge/discharge decision of connected electric vehicles. Smart control of the charge/discharge of EVs can contribute in many ways to the grid stability, it can ensure frequency regulation, prevent peak power consumption, and protect the batteries from deep discharge.

Concerning UC4 and its parking framework, it was shown that the grid type reduces the possible interactions between the functioning of the charging stations and the grid. The possible synergy between a tramway grid and the charging stations appears very interesting for the city of Turin and for the project. The study has shown that it would be useful to add an electrochemical accumulator in order to guarantee the charging service at the fullest even in critical tramway traffic conditions.

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4 CONNECTION WITH DC ELECTRICAL NETWORKS AND WITH TRAM AND METRO NETWORK,

This section concerns task 4.3, which partners are Univ Eiffel, ENEDIS, POLITO, IREN. The main objectives of task 4.3 are to analyse and establish synergies with DC electric and transport networks, especially those of tram and train lines, thus exploiting services triggered by these synergies. This task included :

- A state of the art review about interfacing of power electric chargers with DC networks.
- ENEDIS as DSO carried out a techno-economic analysis, to provide inputs on the optimization of the costs for this solution of DC network integration. In addition, ENEDIS analysed potential synergies with other loads connected to the same LV or MV grid (trams, subway, etc…), assessing what a DC interconnection architecture could bring in terms of grid constraints mitigation and controllability.
- POLITO studied the synergies and advantages due to the DC tram network integration using the Turin city area as reference. In particular: the exploitation of the AC/DC conversion capacity in night hours, with low or zero consumption for public transportation, and the exploitation of vehicle storage for harvesting the power generated during regenerative braking of trams in low traffic hours with reduction of the associated over-voltages.
- Finally, simulations of the connections of Ev chargers to the Turin DC tramway network(use case 4) have been performed;

4.1 State of the art related with electric chargers interfacing with DC networks

Although electricity transmission and distribution networks are mainly designed for alternating current, there is a growing interest for direct current solutions:

- The energy transition is leading to a strong development of native uses of direct current: photovoltaic installations, electricity storage and electric vehicles.
- The proportion of energy consumed by direct current in the home is very high (50% in 2018), and growing strongly (80% in 2030). The consumption vectors are LED lighting and electronics, computers, home automation and variable speed drives for motors.
- Innovation and costs decline in power electronics make the use of direct current and the AC/DC conversion economically viable
- The contribution of DC power is also promising to improve the energy efficiency of a network by reducing the number of connection losses.

4.1.1 DC fast charging stations

DC Fast Charging Stations (DCFCS) are essential for widespread use of Electric Vehicle (EVs). They present the advantage of recharging EVs more rapidly than AC charging stations.

DC charging stations require high-power converters which are capable of charging to 80% in less than 30 minutes. These fast-charging applications require modular power converters which can be paralleled to provide different power levels, thereby enabling fast charging. Such converters generally include 2 stages :

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- The AC/DC stage (also known as the PFC stage) is the first level of power conversion in an EV charging station. It converts the incoming AC power from the grid (380–415 VAC) into a stable DC link voltage of around 800 V.
- The DC/DC stage is the second level of power conversion in an EV charging station. It converts the incoming DC link voltage of 800 V (in case of three-phase systems) to a lower DC voltage to charge the battery of the electric vehicle. The electric vehicle charging standards are governed by standards such as Combined Charging System (CCS) and CHAdeMO. The DC/DC converter must be capable of delivering rated power to the battery over a wide range, for example 50V-500V to accommodate batteries from 48V (e-bikes) all the way up to 400V , with the capability of charging the battery at constant current and at constant voltage mode, depending on the State Of Charge (SOC) of the battery.

DC charging stations have special grid hook-ups so they can get and convert far more power. DC stations are large, expensive and require cooling. CHAdeMO chargers vary from 25 to 100kW, and superchargers are 90 to 250kW. They deliver far more power than standard AC chargers. Typically, the fast AC chargers have a power range from 7 kW to 22 kW, and can charge an electric vehicle in 3 to 4 hours. Slow AC chargers for overnight, household use have a nominal output of about 3 kW and usually require six to 12 hours to charge an electric vehicle. In the case of AC connected electric vehicles, power conversion (AC/DC) is on-board the vehicle.

At higher cost, the grid could supply even more power; but these limits are largely set to avoid harming the car batteries while charging. (Many factors determine how fast batteries can charge, but currently cars that use Superchargers have significantly larger batteries than cars that use CHAdeMO chargers. All else being equal, larger batteries can accept more power without harm)

4.2 Techno economic analysis of solutions for DC network integration

Today, DC electrification appears to be an additional way for connecting emerging appliances, and new connected usages such as renewable and electric vehicles. In comparison to conventional AC networks, DC could provide in some cases advantageous services by introducing power electronics into distribution grid's operation. This enables new services through managing power flows.

In some cases, DC networks could increase the overall efficiency of the installation by providing direct supply to "native" DC users, suppressing, therefore, AC/DC conversion stages at the power delivery point. Thus, instead of multiple conversion units, a central AC/DC conversion is probably more energy efficient. Yet, each application requires a dedicated study before deciding which power type, AC or DC, is more efficient. This could lead to a hybrid AC/DC distribution network as shown in figure 12 below.

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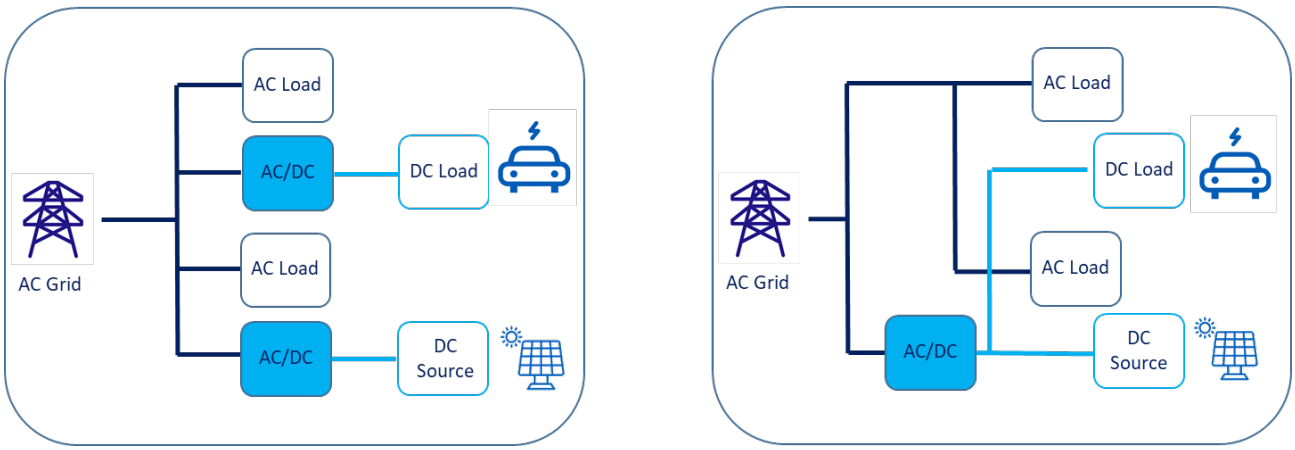

Figure 12. Conventional AC vs hybrid AC/DC distribution networks

DC main advantages over AC would be:

- DC is able to use full peak voltage capability of AC circuits compared to the AC RMS rating
- DC does not suffer from skin effect so there is potential for increased current due to low power losses
- DC will only use 2 conductors instead of 3
- DC will increase the energy efficiency of "native" DC devices

In the task, several case studies of electric vehicle charging infrastructure have been studied, to compare solutions with AC or DC distribution networks, and evaluate the techno-economic benefits of a DC connection for e-mobility. The case studies have concerned:

- Electric vehicle charging infrastructure for parkings in urban areas
- Network for supplying an electric road, which has distributed charging points.

From the analysis of these case studies, it was concluded that DC electrification has several advantages depending on its application. Yet, in some cases, energy efficiency may not be sufficient to justify its usage as shown in the electric vehicle charging infrastructure case study. In fact, in short distance distribution networks, DC will bring benefits regarding flexibility and controllability of local system using power electronics. In addition, in case of high penetration of intermittent power sources or loads, DC can improve local power balance and its impact on the AC grid could be thus minimized.

For long distance applications, such as e-roads, DC reduces lines/cables energy losses, which allows increasing the line's capacity or transmission distance.

Finally, to answer the "DC or AC" question, it was concluded that each case requires a dedicated study to evaluate techno-economic benefits of each solution.

4.2.1 Services associated with a DC electrification

In the future, electric vehicles will probably not be limited to a mean of transport. Due to their energy storage capacity, they are able to consume or inject power into the grid, following request. With vehicle-to-grid (V2G) technology, a car battery can be charged and discharged based on different signals, such as energy production or consumption nearby. In its charging mode, similar to smart charging (V1G), the EV will adjust its power consumption based on instructions received from a control unit (DSO or other). EV, like any

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electricity storage system, will be then an active part of the network that could improve local flexibility and in some cases help reduce grid constraints.

Some services are particular to AC electrification like services related to reactive power or frequency regulation. In DC mode, there is no frequency constraint. Yet, demand-response balance remains a major issue affecting DC voltage stability. EV could then play the same role as in AC mode: reduce its consumption or inject power to the grid in case it is overloaded, store energy in case of an excess of local energy production (ex: high PV production). However, at the same time, using V2G should ensure that EV drivers will have enough energy when they need to use their vehicle.

Services that could be enabled by a DC electrification are more related to the power electronics interfacing of each load/source with the network. These DC/DC, AC/DC and DC/AC converters allow to control power flow through a smart master unit usually called Energy Management System (EMS). The latter will allow implementing advanced control functions and interface the DC local network with the existing AC grid. It enables local services between different components (EV, smart homes/buildings, PV…) and service-to-grid such as:

- Disconnecting from the main grid to improve local resilience: when a fault is detected on the AC side, local energy sources coupled with EV as an ESS could provide a minimum service to the loads.
- Injecting reactive power to boost the voltage on AC side.
- Consuming reactive power in case of over-voltage detection on AC side.
- Support frequency regulation by active power consumption/production.
- Load shedding if the AC grid is overloaded.

4.3 Synergies with DC tram networks

Tramways and light railway systems form one of the most common applications of DC networks worldwide, as they are found on all continents as efficient and reliable means of transport. There are defined standards for tramways and light railway systems, and there are only minimal differences from one system to another.

The two different voltage standards with which these systems operate are 600VDC and 750VDC. The 600VDC standard is more prominent, but systems that are more modern tend to adopt the higher voltage. The DC networks that supply power to trams are often powered by dedicated electric substations with a capacity between about 2 MW and 5 MW. These figures enable the network to function without distress, as the relatively infrequent power consumption caused by accelerations does not require such a high energy.

These networks are therefore prudently oversized and there is a lot of potential energy left to be exploited for other purposes, such as EV recharging. The biggest benefit concerning the potential synergies between a DC tram network and EV recharging lies in the fact that tram networks are generally well distributed in the cities. This is especially true for city centres and their immediate surroundings, where charging points, especially fast chargers, are less likely to be found for various reasons.

A study carried out by POLITO in Turin for the UC4, has shown that even an electrical substation that serves two of the most heavily serviced tramway lines in a relatively large city like Turin and which nominal power output is 2.2MW still has plenty of available power to spare. A 500kW charging hub would pose no real threat to the public transportation service.

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4.4 simulations of chargers interconnected with DC grids – application to the Torino use case (UC4)

In task 4.3, simulations have been performed, to evaluate scenarios of different chargers connected to the DC tram network, for the Torino use case. For that, measurements were carried out, in order to quantify the available energy in the Turin DC tramway network. This grid is a fully meshed network which energy supply comes from 22 electric conversion substations located throughout the city that transform the current from AC medium voltage to DC low voltage. The network is divided into 49 energetically independent areas, and each substation supplies energy to at least 2 of these areas . Voltage and current measurements were made at the Caio Mario substation, which will be used in the use case, which has the following characteristics:

- Nominal continuative power 2.2MW
- Power with a 150% overload for 2h = 3.3MW
- Power with a 200% overload for 60s = 4.4MW

Two different types of measurements were obtained: one with a small time lapse (10ms) and one with a bigger time lapse (0.1s).
The measurements lasted for ten days, and the gathered data was then processed and put into graphs in order to compare them with the pre-existing expectations. There were two main objectives: 1) find out the overall energy consumption of the Caio Mario substation; 2) assess peak and low voltage and current figures. The graph on figure 13 shows the recorded electric consumption. The values are cyclic during the week. There is a pronounced power consumption drop during the night, when no trams are in service. The red line represents the nominal power output of the SSE (2.2MW). 73 cases of overload were measured, always for very brief durations.
After assessing the absorbed power needed to supply the tramway service, the power still available, based on the technical specifications of the station (2.2MW) was estimated. Two different constant loads were added to the total figure in order to simulate the charging hub. The first simulation was made with a 200 kW load (as planned in the INCIT-EV use case), the other with a greater, 500kW load.

The results obtained are shown on figure 14. The two dotted lines show the output increase caused by a 200kW or 500kW EV charging hub, and compare it with the available power. All the blue peaks below the dotted lines indicate an overload of the network. This occurs only during fractions of seconds. With 200kW installed for EV charging, 629 overloads are detected in 10 days, representing only about 1min combined (0.0072% of all measurements). With 500kW installed, there are 5.358 overloads, representing about 9 min (0.062%).

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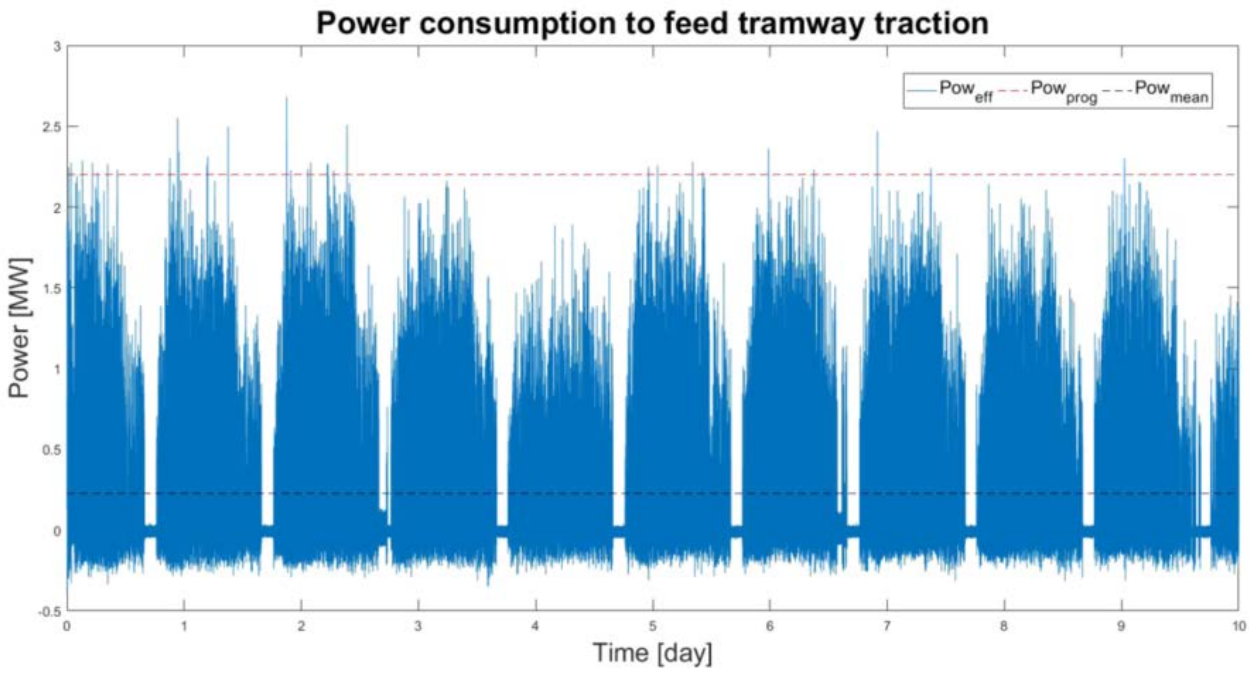

Figure 13. power used to feed the tramway lines

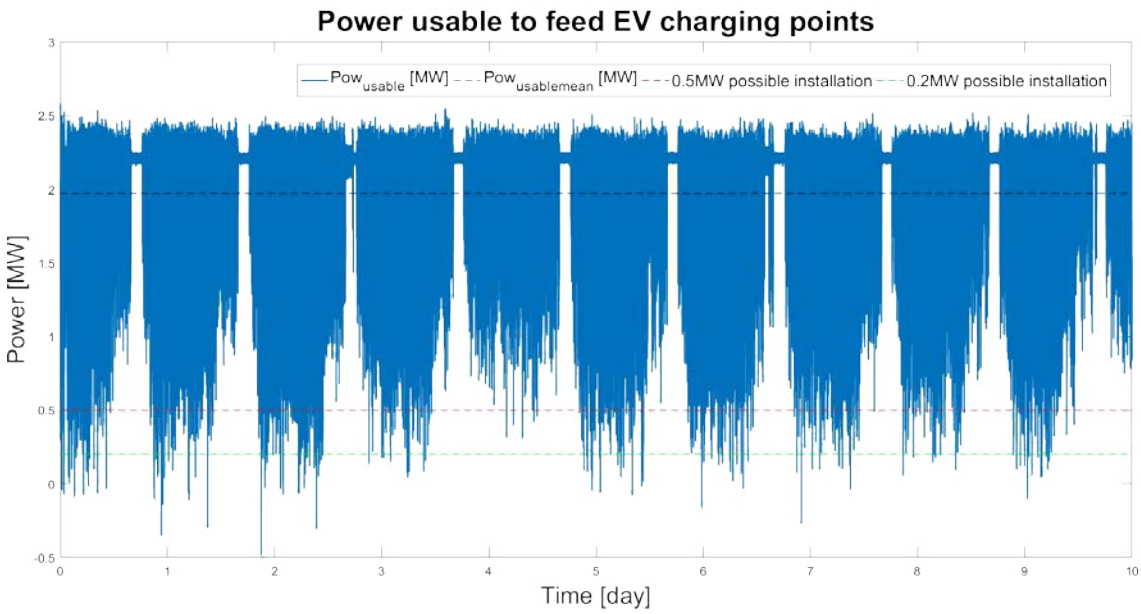

Figure 14. Power usable to feed EV Charging points.

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This analysis shows that there are very few occurrences in which the substation's capacity is overloaded. Even with the 500kW load added, an overload would happen only in 0.062% of the total time. This means that there will be no problem of synergy between public transportation and the planned recharging hub. A means to reduce the overloads would be to add a storage system.

The last part of the simulation tried to assess the usefulness of an electrical storage system to be paired with the substation in order to guarantee peak shaving in the very few high load occurrences, always remembering that the substations' nominal output of 2.2 MW can reach 3.3 MW for 1h and up to 4.4 MW for 1 min. By adding a charging hub (200 kW) to the overall energy consumption of the SSE, the overload occurrences would obviously increase. In order to avoid this scenario, a storage system would be more than welcome. The maximum power recorded was 681.65 kW more than the nominal capability of the SSE, so in this hypothesis the storage system was sized accordingly. Considering the maximum Δt in which the current consumption was greater than the nominal capacity ,this leads to a storage capacity of 0.6817kWh in order to solve the overload for 3.6 seconds (max recorded power output: 2881.65 kW). A second evaluation was done for a charging hub's power of 500 kW. In order to avoid the overload scenario, the storage system needs to be sized for a 981.65 kW overload with a Δt of 5.9 s. The result is a 1.6088 kWh storage system capacity in order to deal with a total max output of 3181.65 kW.

Therefore, a modest electrical storage system with a 1.6088 kWh capacity would guarantee the draining of 981.65 kW for 5.9 s. The best possible choice in this sense would be a supercapacitor, which capability to deliver a high power in small time frames would be ideal.

In conclusion, the analysis of this use case showed that:

- There is a significant amount of energy to be exploited in the SSE Caio Mario. There are indeed moments with high energy loads, but they are of very short duration. A storage system would erase all the potential concerns.
- From a voltage standpoint, there were no dangerously high spikes that could put the EV charging hub in jeopardy.

4.5 Challenges of deployment of EV charging facilities connected to DC grids

Although electricity transmission and distribution networks are mainly designed for power alternating current, strong trends point to direct current, mainly in connection with the energy transition, which is leading to a strong development of native uses of direct current: photovoltaic installations, electricity storage and electric vehicles. These uses have a significant impact on distribution networks. Therefore, DSOs should pay attention to DC network architectures and prepare future ways of connection, case by case, looking at costs, benefits and risks in developing further DC networks.

More specifically, the development of MV or LV direct current networks does not seem likely in the medium to long term. Indeed, there is no standard of architecture neither voltage level, and equipment off the shelf is often not available. In any case, future DC expansions will have to cohabit with the installed AC grids, which

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make the DC both technically and economically challenged. Other technical challenges for grid integration, when designing a DC distribution network, are listed below

Protection :

One of the main concerns in DC electrification is building a protection system that could give similar performance as in AC mode and the main challenge remains ensuring selectivity. The selected architecture (monopolar, bipolar, isolated or not from the ground) has major impact on the power protection plan. For example, protection requirements in a closed electrical circuit only accessible to qualified technicians (datacenter, PV installation…) are different from a public distribution grid and it's possible to isolate the network from the ground. Yet, whenever a random person can get a direct contact with the grid, a grounded system is necessary to guarantee safety.

Metering :

In the end of 2015, the European commission launched the mandate M/541 asking normalisation organisations CENELEC, CEN and ETSI to work on norms specific to electric mobility, related to the European directive 214/94/EU that helps increasing EV integration in the EU. The expected result was one or several norms related to legal metrological control of energy supply to public consumers in AC and/or DC, including on-board meters for e-mobility application.

Following this request, a new norm project for DC metering was drafted. The IEC 62053-41 entitled "Electricity metering equipment (DC direct current) – Particular requirements – Part 41 – Static meter for active energy (class 0.5 and 1)". This future norm will be applicable to the following scope:

- meters for bipolar DC networks, with one connected to the ground and with voltage up to 1500 VDC
- Possible applicable areas include in particular : PV systems where energy is measured in DC, Electric vehicles charging infrastructures or stations in the case where measurement is done on the DC side, Public DC transportation
- It applies to static meters for active energy, and directly connected meters. In order to respects the general requirements of existing metering norms, the maximum voltage level Umax ensuring safety is set to 600V and the maximum current Imax to 160A for meters connected directly.

Stray currents :

A well-known problem in DC railway systems, stray currents are a major issue to be considered when it comes to DC. In fact, DC stray currents are currents that will leave their normal path and go through other metallic components located nearby and then come back to their normal path. When leaving a metal, for example a grounding plate, DC stray currents will cause its corrosion, which could lead to serious damages like gas leakage due to corroded canalization but also losing an electrical grounding reference.

In DC electrical distribution, the operator should make sure that his system has no impact on other infrastructures. A special attention should be given to junction boxes, cables passing in reinforced concrete…, especially that the latter is usually connected to the grounding system, in general the same as the electrical system. Note that stray currents also exist in AC but due to the waveform (positive and negative alternation), its impact can be neglected.

DC ready loads :

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Today, because the network is mainly in AC mode, only few equipment on the market are DC ready (very Low voltage applications such as IT systems and lights, PV, batteries…) especially in Europe. For example, if we decide to deliver today DC power to a new tertiary building, a DC/AC converter is mandatory to power most of its main loads (HVAC, elevators, coffee machines …). It would be even more difficult if it is a residential building where it is not acceptable to ask residents to buy DC compatible devices that may not exist on the market. Thus, DC distribution is possible today only for particular cases such as EVRI where the owner can afford customized equipment.

Dc power quality:

Same as AC grids, DC grids must fulfil power quality requirements to guarantee reliable operation. However, knowledge about power quality in public DC systems and its impact on DC electricity metering and usage is still missing, as is the related metrology and standardisation. Standardization working groups and European projects are currently working on these aspects to contribute to the revision of concerned standards such as EN 50160, IEC 62053-41…

4.6 Conclusions of task 4.3

This task has highlighted the benefits of developing DC electricity networks, in particular for applications linked with the energy transition, which often use direct current. It has developed a state-of-the-art and an analysis about the advantages offered by connections with DC networks and integration with tram/metro energy lines in different contexts, for charging vehicle infrastructure.

The work has shown that energy efficiency is sufficient to motivate DC connection usage. In short distance distribution networks, DC can also bring benefits regarding flexibility and controllability of local system. Moreover, in case of significant impact of intermittent power sources or loads, DC can allow improving local power balance and then minimising its impact on the AC grid. Regarding long distance applications, such as e-roads, DC reduces energy losses in lines or cables, which allows increasing the line's capacity or transmission distance.

In order to analyse the compatibility of connecting charging infrastructure to a tram DC network, the current and voltage variation at the SSE Caio Mario were measured and analysed. These analyses showed that there is a large amount of energy to be exploited in the SSE Caio Mario. Moments with heavy loads of energy are rare and spaced in time. By associating a storage system, these moments of heavy demand could be managed. Looking at the voltage variation, no dangerously high spikes, that could put the EV charging hub in jeopardy, were observed. Moreover, no true overvoltages were recorded during the measurement campaign.

Finally, in addition to these analyses, specific problems, in terms of safety or protection, associated with direct current have been highlighted, and some solutions have been identified.

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5 TASK 4.4 - INTEGRATION OF DYNAMIC WIRELESS CHARGING SYSTEMS IN ROAD INFRASTRUCTURES

5.1 Introduction

This section concerns task 4.4, which partners are Univ Eiffel, Vedecom, Eurovia, Colas, Polito and MRA-E. The objectives of task 4.4 are to define and develop solutions for integrating the wireless dynamic charging systems developed in INCIT-EV in roads. These solutions will then be implemented in the demonstrators developed in work packages 7 and 8 of INCIT-EV. The work of task 4.4 concerns two wireless charging systems developed in INCIT-EV.

- The system developed by VEDECOM, for urban applications, which will be installed in the Paris demonstrator, built in WP 7.
- The system developed by CIRCE, for inter-urban applications, which will be installed in the Satory demonstrator, built in WP 8.

From the road infrastructure's perspective, the integration of wireless charging technology in roads raises several important issues:

- The development of appropriate construction methods, to ensure satisfactory mechanical properties and protection of the charging system components, and reasonable cost.
- the effect of the surrounding materials on the charging efficiency of the Wireless Power Transfer (WPT) system, i.e. the power loss caused within the road structure when alternating magnetic fields pass through it;
- the influence of the embedded charging components on the structural performance of the road under operational conditions;
- the consideration of the maintenance needs of the charging system (access to some components) and of the road itself (renewal of the surface layer for example).

The work performed in task 4.4 of INCIT-EV, to prepare the road integration, has consisted in :

- Making a review of existing dynamic wireless power transfer (DWPT) systems, with a focus on integration of these solutions in road structures.
- Reviewing the characteristics of the Vedecom and CIRCE charging systems, and proposing possible solutions for their integration in roads.
- Carrying out a laboratory test program, for testing solutions for the integration of the charging modules in pavements, to ensure satisfactory charging performance, durability and resistance to traffic loads and to climatic effects (temperatures, moisture).

A summary of these different tasks is presented in this section. A more complete presentation is available in deliverable D4.10 "Road infrastructure upgrading for dynamic wireless charging".

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5.2 Review of existing wireless power transfer systems, and of solutions for their integration in pavements

5.2.1 Main elements of dynamic charging systems

Inductive charging is a new way of charging of electric vehicles in opposition to conventional chargers, where charging is made by means of plugs and cables. Inductive charging uses the principle of magnetic induction, to transfer an electric current. The chargers are composed by coils and charging is achieved without contact, when the two coils are close to each other.

Inductive charging technology can be used to perform dynamic charging when the vehicle moves. It requires the installation of coils inside the road infrastructure and their supply by an appropriate electric power grid. The main challenge today is to develop interoperable systems, to ensure the compatibility between solutions developed by different manufacturers

Each use case of the technology imposes different constraints that need to be taken into account to adapt the system to maintain efficiency and cost. In the INCIT-EV project, the objective is to develop dynamic wireless charging systems **for light and half-duty vehicles, for urban and extra-urban use cases**.

An inductive charging system includes the following main components (see figure 15):

Power grid: the system is grid connected and depending on the power, it needs to have a triphasic or monophasic connection.

PFC: The power factor corrector device is not only responsible for improving the quality of the grid connection but also to adapt the AC voltage to a DC voltage to power the inverters. The PFC will generate a DC bus and its localisation is important to reduce the voltage drop in the track and also to reduce the losses.

Inverters: These are the most complex devices because they are responsible of communication, control and regulation of the power transfer to the vehicle. In best conditions, they require easy access for maintenance, and possibilities of cooling, to dissipate the power losses.

Resonant circuit and coils: The resonant circuit and the coils are composed by passive elements that will be powered by the inverter. The resonant circuit allows to compensate the inductance of the coil and provide the resonance condition. In most systems, high voltages are generated on the terminals of both elements. Because of that, these elements need to be near each other. Normally they are constructed together to avoid electrical isolation problems. The coil is the key element responsible for the magnetic field generation, and therefore its size, precise geometry and localisation are primordial to ensure safety and good power transfer rate.

AC/DC converter: This converter is inside the vehicle and is used to adapt the power received by the on-board resonant circuit and coil to recharge the battery of the vehicle.

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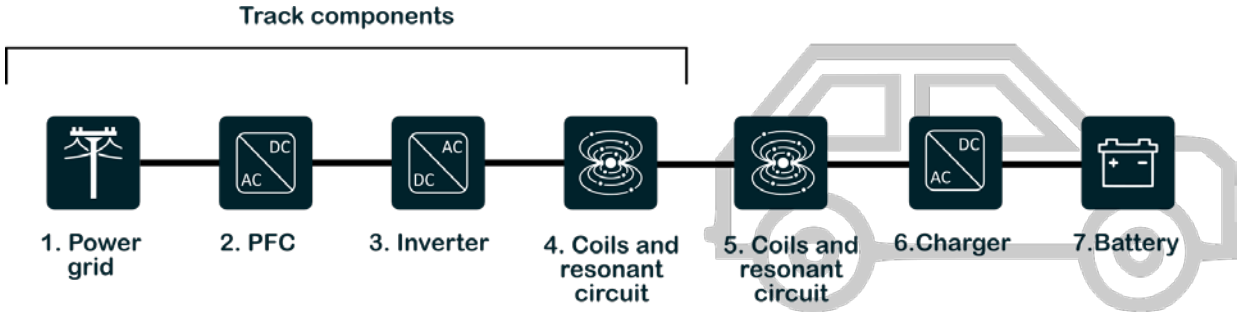

Figure 15. Main elements of a dynamic wireless charging system

Road Integration issues

From the point of view of road integration, this architecture imposes several constraints:

- The primary coils and resonant circuits must be embedded in the pavement, in the middle of the road lane, and at low depth (maximum about 10 cm, and if possible less), to minimize the gap between the primary and secondary coils, to ensure maximum power transfer. When operating, the primary coils generate heat, which must be compatible with the materials used in the pavement structure.
- The inverters (generally one per coil), must be placed close to the coils, and remain accessible for maintenance. They must be connected to the coils, and also interconnected, for communication. Finally, these elements heat-up and the generated heat must be dissipated.
- Because a road is never completely impervious, all the components integrated in the road (coils, resonant circuits, inverters, and associated cables and connectors must be fully waterproof, and resist to immersion in water.
- The PFC (power factor corrector) which is a larger equipment, can be located above ground, to remain accessible, and should be placed in a central position, to minimize cable lengths.

5.2.2 Pavement structures and pavement materials

A pavement structure can be defined as the superposition of layers of different materials, designed to distribute traffic loads on the subgrade. The different layers forming the pavement structure are shown in Figure 16. They are designed to allow the movement of traffic, and to ensure the safety and comfort of road users [3].

The pavement layers consist mainly of 3 main elements

The Surface course: It is the uppermost layer of the pavement structure. It may consist of two layers: the wearing course and the binder course. The wearing course is designed to resist to the effects of climate and traffic, and to ensure a good riding quality of the road (evenness, skid resistance).

The Road base: The road base generally consists of two layers, the base course and the subbase. These layers provide the mechanical resistance to the vertical loads induced by traffic and distribute the stresses on the subgrade.

The Subgrade: It is the lowest layer in the pavement structure. It is the compacted natural soil immediately below the pavement layers and acts as a foundation for the highway. The subgrade may be surmounted by a capping layer, which is used to improve the homogeneity and bearing capacity of the subgrade.

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Figure 16. Composition of a pavement structure

Pavement structures are mainly built with two types of materials :

- **bituminous material** : They are composed of aggregates (in several fractions), hydrocarbon binder, and, if necessary, additives. A typical bituminous mixture is composed of around 5% of binder and 95% of aggregates by mass. Bituminous materials behave (at small strains) like visco-elastic materials, and their behaviour is very sensitive to temperature and loading frequency. In pavements, their main modes of deterioration are permanent deformations (rutting), occuring at high temperatures, and cracking , generally due to fatigue, or thermal variations.
- **Cement treated materials or concretes** : These materials are a mix of aggregates, cement or other hydraulic binders and water, and if necessary some additives. They can be divided into road concretes, which typically contain between 5 % and 12 % of cement, and granular materials treated with hydraulic binders, with lower percentages binder (between 3 % and 5 %). Road concretes have higher mechanical properties. These materials are manufactured in a mixing plant, and put in place cold, contrary to bituminous materials. They have the property of hardening with time, after mixing, and generally need at least 28 days to reach their final mechanical properties. They present a merely elastic behaviour at low strains, and contrary to bituminous materials, their behaviour is not sensitive to temperature. These materials present a high mechanical resistance, and are used mainly for base layers of heavy traffic pavements. Due to their high stiffness, the main mode of deterioration of materials treated with hydraulc binders is cracking, which can be due to shrinkage fatigue, and thermal variaions.

In the INCIT-EV project, the chargig systems will be integrated in **bituminous pavements**.

Electromagnetic properties of pavement materials

The WPT systems use a magnetic field to transfer power to the vehice. Therefore, the performance of these systems will be influenced by the electromagnetic properties of the surrounding pavement materials. The properties to consider are :

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- electric resistivity ρ,
- relative electric permittivity ε_r,
- relative magnetic permeability μ_r

A review of electromagnetic properties of pavement materials has been performed and can be found in deliverable D4.4. Typical orders of magnitude of these properties are summarised in table1.

Table 1. Orders of magnitude of electromagnetic parameters of bituminous materials

Characteristic	Values	Comments
Electric resistivity ρ,	10^{7} to 10^{13} Ω.m (for dry materials) 10^{3} to 10^{6} Ω.m (in water)	Parameter sensitive to mix design and moisture content
Relative electric permittivity ε_r,	4.5 to 6.5 for dry bituminous mixes 2.5 to 3 for bitumen	Sensitive to aggregate nature and water. Moisture strongly increases permittivity, especially at low frequencies
Relative magnetic permeability μ_r	Very close to 1	Pavement materials are generally non-ferro-magnetic, and their magnetic permeability is close to that of vacuum

5.2.3 Solutions for pavement integration

Because the primary coils of WPT systems need to be embedded in the road, conventional road structures need to be modified, to integrate these systems. Such structures will be called E-roads in this report. Three main types of designs can be found in existing WPT systems [4] :

1. Trench-based construction (built in situ, or with prefabricated elements);
2. Micro-trench based construction;
3. Full lane-width construction, (built in situ or made of prefabricated elements)

5.2.3.1 Trench-based construction

Trench-based construction consists in placing the WPT coils in a trench made in the asphalt layer, which is then generally filled with concrete. This structure is then generally covered with a bituminous wearing course. Figure 17 shows a cross section of a road for a trench-based electric road implementation. The trench-based construction is quick to complete, has a moderate cost, and can be used to install the WPT systems in an existing pavement. The concrete elements placed in the road can be prefabricated. This solution offers several advantages: the position of the different components of the charging system can be precisely controlled, and the installation is easier.

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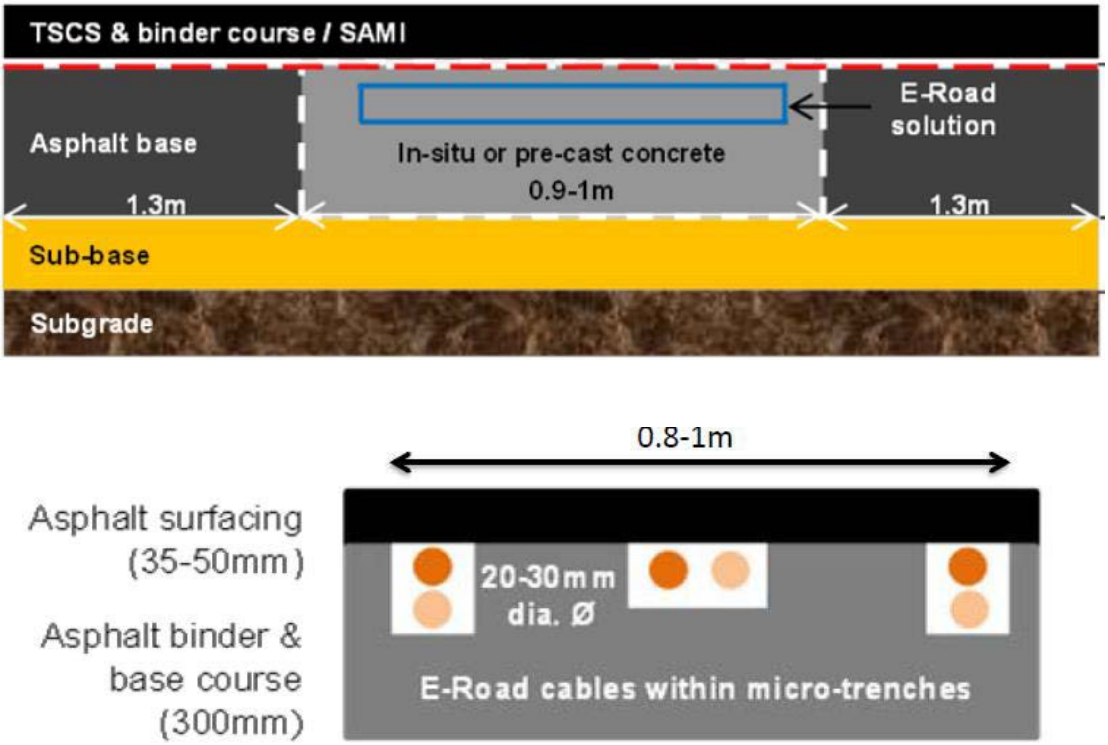

Figure 17. Trench-based construction (top) and micro-trench–based construction (bottom) for integration of WPT

This type of integration solution has been used in several recent inductive charging systems (Bombardier, KAIST-OLEV)

5.2.3.2 Micro-trench based construction

Compared with trench-based construction, the micro-trench architecture uses narrow, shallow slots in the existing structure, thereby causing less damage to the existing road structure. Figure 17shows a cross section of road integrating a micro-trench based solution. Similar to the trench-based construction, it is cheap to construct, and can be used on existing pavements; however, depending on the material used for filling the trenches, the protection of the cables may be less efficient than with the wide concrete trench.

5.2.3.3 Full lane-width construction

Trench-based constructions create grooves and trenches in the existing road structure, which can be a source of cracking and deterioration. In contrast, full lane-width constructions incorporate the coils in a concrete structure covering the full width of the road (see Figure 18). Full lane-width construction can be built in situ or prefabricated. However, full lane-width construction takes more time and is more expensive than trench based construction, and it is mainly adapted to new construction. The advantages of precast full lane-width construction is reduced installation time and more precise positioning of the charging elements. However, the precast concrete slabs require to create longitudinal joints, to avoid uncontrolled cracking of the concrete structure. These joints can be a source of deterioration, an require maintenance

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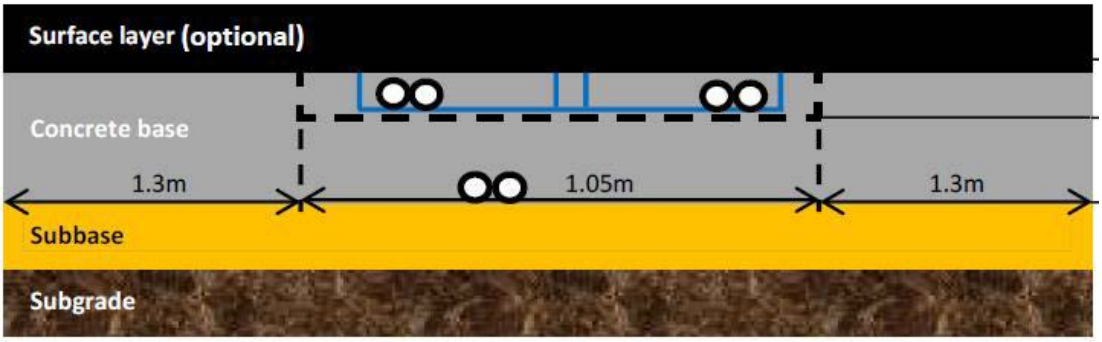

Figure 18. Full lane-width construction for integration of WPT system.

In summary, classical road materials can be used for E-roads, and different types of construction can be used, depending on the projects (new construction or installation in an existing pavement), complexity of the charging elements and tolerances for their positioning.

However, several aspects require special attention:

- The integration of the charging system in the pavement creates discontinuities and joints between materials with different mechanical and thermal properties, and can lead to cracking and deterioration. Good bonding between the inclusions and the pavement materials is essential to achieve good performance.
- The WPT systems must be installed at low depth below the pavement surface (ideally about 5 to 6 cm), to limit the gap between the primary and secondary coils. This means that they will only be covered by a thin wearing course. This can create a risk of fatigue and cracking of this upper layer.
- Due to their electromagnetic properties, pavement materials can affect the performance of the charging system, especially if they contain water. Therefore, it seems necessary to use nonconductive materials as dielectric between the WPT coils and the surrounding road materials.

5.3 Review of existing wireless power transfer solutions.

In deliverable D4.4 of INCIT-EV, a detailed review of different existing wireless power transfer solutions has been carried out, with a focus on pavement integration aspects. In particular, solutions developed by Polito [5], Bombardier (Primove system , [6]), by the Fabric project [7, 8], by KAIST-OLEV [9, 10], by CIRCE (Victoria project, [4]) and by Electreon [11] have been studied. Only a summary of the conclusions of this study is presented in this section.

A summary of characteristics of some of these charging systems is given in table 2 below [12].

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Table 2. Comparison of characteristics of different WPT systems [13]

Year	Project	Veh. Type	Driving Cond	Air Gap cm	Max Power kW	Op. Freq. Hz	Eff. %	Ref. and Outcomes
1980s	PATH UC Berkeley	Bus	Dynamic	5–10	200	20	60	Ref. [29] Project Stopped
1997	Conductix-Wampfler	Bus	Static Stationary	4	30	15		Patents [30,31] First commercialized static WPT
2011	SELECT Utah State University	Bus	Static Stationary	15–25	25	20	90	Ref. [32] Commercial activities (WAVE)
2011	PRIMOVE Bombardier	Bus	Static Stationary Dynamic		200	20	>85	Ref. [33] Commercialization static systems in Mannheim, Berlin
2011	KAIST Olev	Bus	Static Stationary Dynamic	15–20	100	20	85	Ref. [34] First commercialized dynamic wireless charging bus
2016	ONRL	Pass. car	Slow dynamic		20	22–23	90	Ref. [35] Research Laboratory conditions
2017	FABRIC Versailles-Satory Site	2 serial Pass. cars	Stationary to highway speed (100 km/h)	17.5	20	85		Ref. [36] Experimental representative road

From the point of view pavement integration, the review of different inductive charging systems has led to the following main conclusions :

- The tested systems include both urban and interurban applications.
- The primary coils (integrated in the road) vary greatly in length, from less than 1 meter to 24 m long.
- Some systems are dedicated to buses or heavy vehicles, whereas others are suitable for different types of vehicles, from cars to heavy goods vehicles.
- Different architectures are also used, with one inverter controlling only one coil or several coils.
- Easy access to the electronics seems important to facilitate maintenance and adaptation of the systems
- Typical air gaps between the primary and secondary coil seem to range between 15 cm and 25 cm
- Integration in both bituminous materials and concrete materials has been tested, and both seem possible. Several projects have used prefabricated concrete solutions, which present the advantage of a good control of the geometry of the components and easy installation.
- The most frequent mode of construction seems to be the trench-based construction, where the system is installed in a trench (about 0.6 to 1 m wide), milled in the centre of the road lane, and then covered with a wearing course extending over the whole road lane, to ensure a smooth riding surface, without joints. This type of solution limits the volume of construction works.

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- Problems of electromagnetic influence of the road materials are mentioned in some projects; it is clearly necessary to avoid materials containing ferrous elements, and moisture also has a negative effect. A solution to reduce these problems is to protect the coils with a dielectric insulating material.
- The heat generated by the system in operation can be significant, and can affect materials sensitive to temperature (in particular bituminous materials).
- Practically no information could be found about the long-term durability of the pavement solutions, and observed deteriorations, probably because these applications are too recent.
- Finally, metallic object detection in the charging area (due to the heating effect of induction) is mentioned as a very important issue in the Bombardier demonstration.

5.4 Description of the VEDECOM and CIRCE charging systems

In INCIT-EV, two dynamic WPT solutions are developed, for two different use cases: the urban solution (UC2) is developed by VEDECOM, and the interurban solution (UC3) is developed by CIRCE. The two systems are intended for passenger cars and light utility vehicles (<3,5 T).

This section presents some of the main characteristics of the two developed systems, and of the associated demonstrators.

5.4.1 VEDECOM system description

A schematic description of the primary system of the Vedecom solution is shown on figure 19. The primary includes:

The DC power source: Connected to the grid, this AC-DC converter will power the whole system with a constant DC voltage and current.

The inverter modules : Each module is composed by electronics and power electronics circuits and it is responsible for the power electronics command, electrical measurements and communication with the next and previous inverter modules of the track but also with a track supervisor interface.

The coils: They are the wireless power transmitters and are composed by an inductance and a capacitance. The VEDECOM coils are 1m long, and have a power of 30 kW.

A detailed description of the VEDECOM system, including its electrical characteristics, can be found in deliverable D 3.4 of INCIT-EV.

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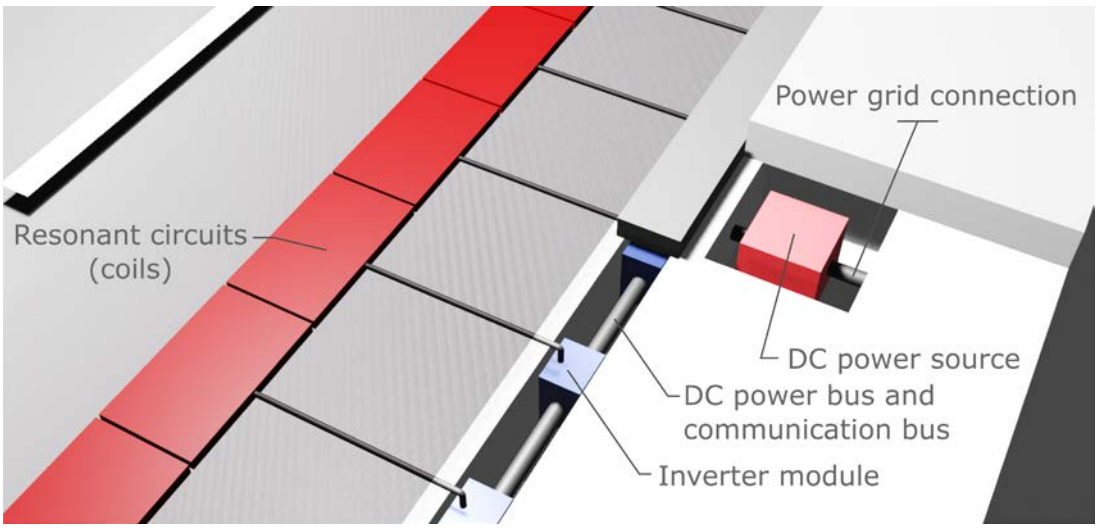

Figure 19. Schematic description of the VEDECOM primary charging system.

A sketch of the coils developed by VEDECOM is shown on Figure 20. The coils include :

- 7 loops made of Litz wire
- Capacitors, placed on the side of the coils
- Ferrite plates, placed below the litz wire loops, to orientate the magnetic field, and limit losses.
- A support, made of insulating and resistant material, which covers and protects the different elements. After testing of different materials, this support will be made of a rigid polyurethane.

The dimensions of the coils are 1 m long by 70 cm wide and approximately 4.5 cm thick.

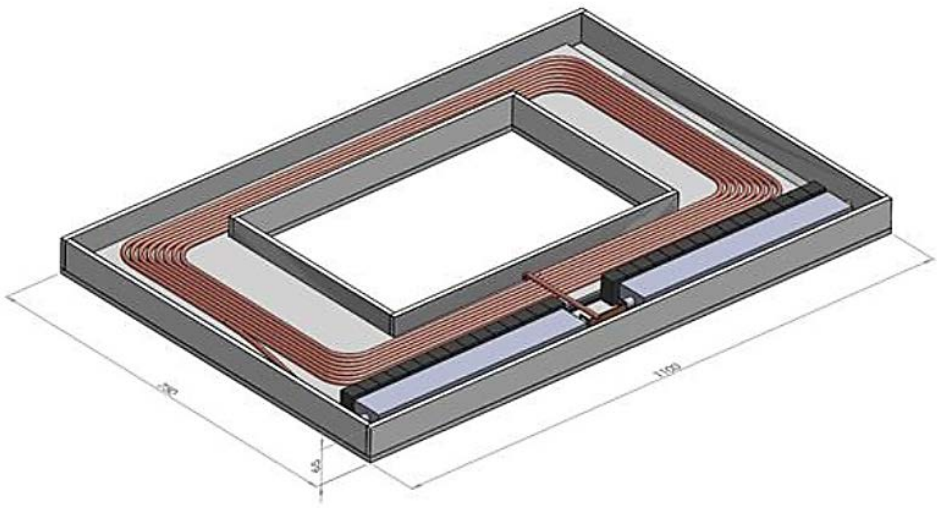

Figure 20. VEDECOM coil design.

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For the urban demonstrator, it is planned to install two 25 m long charging sections, with a total installed power per section of 120 kW (30 kW per coil). The operating speeds will be between 0 and 50 km/h.

5.4.2 CIRCE system description

The charging system developed by CIRCE for inter-urban applications represents a challenge according the current technical literature as It consists to feed up to three possible 30 kW secondary coils while running at high speed (130 km/h). The solution is based on 10m long and 45 cm wide coils, with a power of 90 kW per coil and the total length of the charging section will be between 80 and 90 m. A schematic description of the CIRCE primary system is shown on figure 21. The primary includes:

- One AC/DC converter, for the supply of all the coils;
- 4 DC /AC high frequency converters (1 for two coils);
- 8 coils (10 m long), made of Litz wire. Each coil consisting of only 1 loop of Litz wire, with a large section (around 200 mm^2), and associated capacitors.

The CIRCE system is designed to simplify as much as possible installation, and to reduce costs, for the long-distance application. The objective is to use no ferrite and no aluminium in the road structure, and no cooling system. A detailed description of the CIRCE system, including its electrical characteristics, can be found in deliverable D 3.4 of INCIT-EV

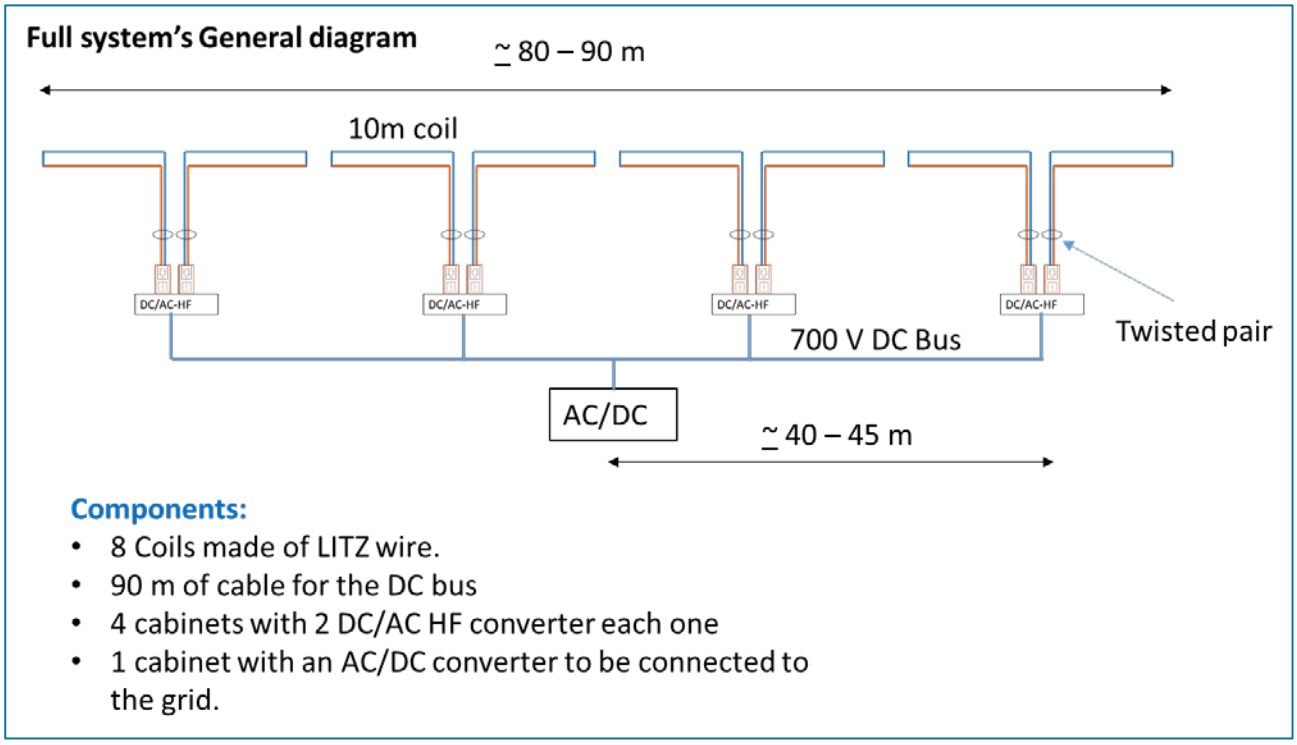

Figure 21. Schematic description of the CIRCE primary charging system.

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The inter-urban demonstrator will be a dedicated test track, built on the site of VEDECOM, in Satory. The charging section will have a total length of about 80 meters, and will include eight 10 meter long coils. The total installed power will be 360 kW (90 kW per coil). The operating speeds will be between 0 and 130 km/h.

5.5 Work program for road integration of WPT systems at laboratory scale

5.5.1 Methodology for road integration of WPT systems

Based on the state of the art and review of existing solutions, a methodology has been proposed in task 4.4, for studying the integration of WPT systems in pavement structures, at laboratory scale. This work is carried out in collaboration with task 3.4, in charge of the design of the WPT systems. The main steps are the following:

- **Definition of the type of pavement structure**. Depending on the characteristics of the primary coils, on the use case and type of pavement structure, a first initial design is proposed, for the integration.
- **Selection of appropriate materials**. The second step consists in selecting a suitable protective and insulating material for the coils, and suitable pavement materials.
- **Laboratory testing**. The objective is to evaluate, in realistic laboratory conditions, the performance of the primary coils, embedded in pavement materials. Several aspects need to be studied :
    - The electromagnetic performance of the coils embedded in pavement materials (dry and wet).
    - The temperatures attained when the charging system is in operation.
    - The resistance of the coils to the construction process, and then to traffic loads.
- **Mechanical and thermal modelling.** Modelling is performed to evaluate temperatures in the E-road, and mechanical behaviour of the E-Road under vehicle loads.

5.5.2 Proposed pavement structures

In task 4.4, the objective is to develop solutions for pavement integration of the Vedecom and CIRCE charging systems in bituminous pavements. The proposed integration solutions are described below :

5.5.2.1 Urban demonstrator (Vedecom system)

The proposed solution consists in milling a narrow trench in the existing pavement, just slightly larger than the coils, and installing and sealing the coil in this trench with an appropriate joint material (resin), and then covering this trench with a surface layer, covering the whole width of the road lane (see figure 22).

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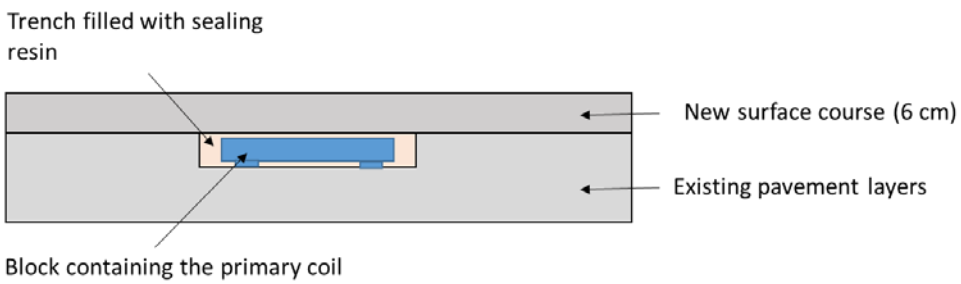

Figure 22. Narrow trench solution for pavement integration (urban demonstrator)

The following remarks can be made about this solution :

- This solution is simple to build, and the surface layer, covering the full width of the road lane avoids the presence of joints on the surface.
- The resin used for sealing the coils is a key element of this solution : it must ensure a good bonding with the coils and pavement materials, and it must be sufficiently flexible to limit risks of cracking due to the different properties of the pavement and coil materials.
- Because the asphalt materials are laid at high temperatures (about 160 to 180 °c), the resin, and the insulating material protecting the coils must be able to resist to thee high temperatures.

5.5.2.2 Inter-urban demonstrator (CIRCE system)

The solution proposed for the inter-urban demonstrator is relatively similar to the one proposed for the urban demonstrator (see figure 23). This solution consists in milling a wide trench in the middle of the road lane (about 1 m wide minimum), fixing the coils to the bottom of the trench, and then filling directly the trench with a specifically designed, easily compactible asphalt concrete.

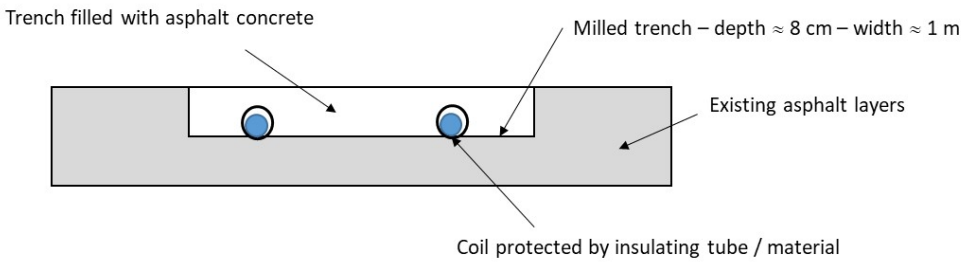

Figure 23. Wide – trench solution for pavement integration (inter-urban demonstrator)

The following comments can be made concerning this solution :

- This solution is simple to build : the trench (1m wide minimum) is easy to mill, and only asphalt material is used. Instead of a trench, it is also possible to mill and replace the whole width of the road lane, to avoid joints.
- The Litz wires need to be protected by a coating material which is waterproof, insulating and resistant to temperature (160 °C to 180 °C).

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- During construction, the coil will be directly in contact with the hot bituminous materials (160 °C), and directly submittted to the stresses generated by the compaction of the bituminous material. It will be necessary to verify that the coils are sufficiently protected by the coating material, and will not be damaged by this process

5.6 Laboratory testing for the Vedecom system

To evaluate the Vedecom solution, a program of laboratory test, developed specifically for the INCIT-EV project, was carried out. It includes:

- Measurements of the charging performance of the coils, with pavement materials
- Measurements of thermal behaviour of the coils embedded in pavement materials
- Measurements of the mechanical properties of the materials, and resistance to wheel loading of the embedded coil elements (at small scale)

This summary report presents only some main results of this study. The detailed test results are presented in deliverable D 4.10. The test program is also completed by finite element calculations, performed to model the thermal and mechanical response of the charging coils embedded in the pavement, presented in § 5.8.

5.6.1 Testing of charging performance with asphalt and concrete materials

A first series of tests was performed to evaluate the charging performance of the Vedecom coils, first with air between the primary and secondary coils, and then with plates of pavement materials (asphalt concrete and also cement concrete) placed between the primary and secondary coils.

These tests were carried out on a test bench, specificallly developed by VEDECOM for the testing of WPT systems. This test bench consists of a platform, where the primary coils are installed, and a robotized arm, which is used to move the secondary coil, to simulate the moving vehicle (see figure 24).

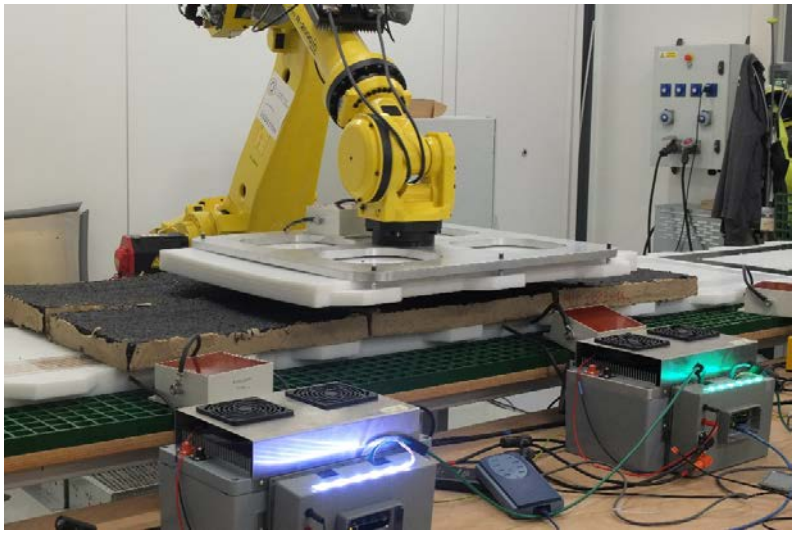

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Figure 24. Charging performance tests with the bituminous concrete plates.

The tesst were performe with six plates of cement concrete and six plates of bituminous concrete, with dimensions of 600 mm long x 400 mm wide x 50 mm thick. The materials selected were a standard road concrete and a standard wearing course bituminous concrete (EB-BBSG). The cement concrete is composed of Gneiss aggregates (0/11.2 mm grading), with a cement content of 325 kg/m^3, and with a compressive strength of 51 MPa. The bituminous concrete is a standard French wearing course material (EB BBSG) , with a 0/10 mm grading, made with diorite aggregates (la Noubleau quarry) and a classical grade 35/50 pure bitumen (content 4.94 % by mass).

To test the influence of the materials, charging tests were performed with different distances between the primary and secondary coils, and different conditions of alignment between the coils (up to +/- 25 % misalignment). The different tests performed with each material are summarised in table 3.

Table 3. Program of the material compatibility tests

Distance between the coils	10 cm, 15 cm, 20 cm, 25 cm
Alignment	-25 % to + 25 %
Input Power	20 kW
Materials	Bitumen, concrete, air

During the tests, the input power, the output power, and the charging efficiency were measured. The results indicated that :

- Overall, the charging efficiency was very good for all the test conditions, with values of efficiency varying beween 85 % and 90 %
- the charging efficiency was only very slightly reduced (by about 3 %) when 5 cm plates of pavement materials were placed between the coils, compared to results obtained in air.
- The effect of the misalignement between the coils (+/- 25 %) was also very limited, with a decrease of about 3 % of the charging efficiency.

In conclusion, in these tests, the influence of the pavement materials (bituminous concrete or cement conrete) on the charging efficiency appeared very limited.

5.6.2 Testing of charging performance and temperature variations with granular materials.

Aftre the first tests, a second series of tests was started , with the coils embedded in pavement materials. These tests were performed with the coils embedded in a granular material, without binder, identical to the granulal skeleton of the bituminous concrete. The advantage of using a granular material is that it has no cohesion, and that the coils can be easily embedded in the material and removed.

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The experimental setup for these tests is shown on figure 25. The granular material was placed in a plastic container. A first layer of granular material was placed at the bottom of the container and compacted. Then, the primary coil was placed over the granular layer, and covered again with a layer of 5 cm of granular material . During the embedment, 6 temperature sensors were placed in the container at different depths, to measure the operating temperatures during the charging. Finally the secondary coil was installed above the embedded primary coil, using plastic supports.

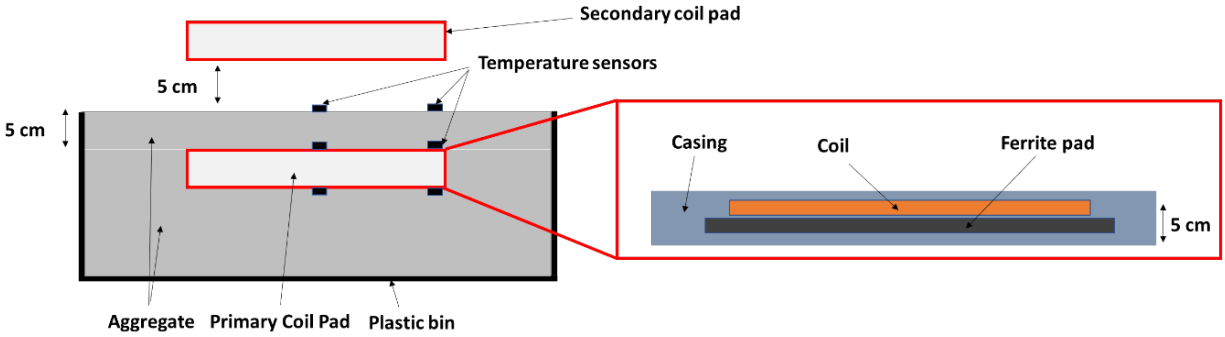

Figure 25. Experimental setup for the tests with a granular material

Several tests were performed with this setup :

- Temperature measurements, with different charging sequences.
- Charging efficiency measurements with a dry granular material.
- Charging efficiency measurements after wetting of the granular material, with a water content similar that expected on site (about 3 % of water).

The tests consisted of carrying out cycles of 3 minutes of charging / 3 minutes of shutdown (to simulate intermittent charging on site) for 1 hour, 2 hours and up to 5 hours, with a power supply of 15 kW. The real field power level (30 kW) could not be simulated. The temperatures were measured after 1 hour, 2 hours and 5 hours (after stopping the charging). The positions of the probes are recalled on figure 25.

Figure 26 shows an example of evolution of temperatures measured as a function of time, with the different temperature probes.

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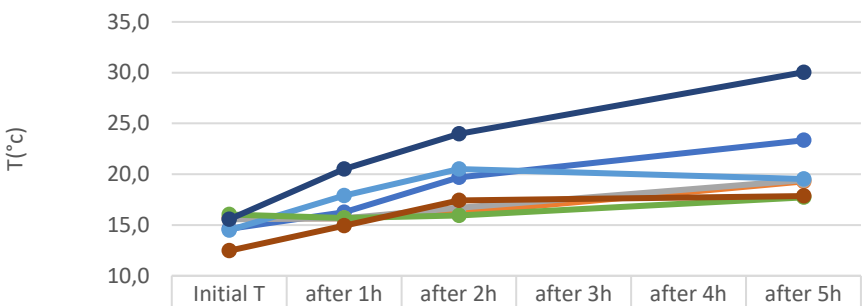

	Initial T	after 1h	after 2h	after 3h	after 4h	after 5h
Probe 00	14,62	16,26	19,70			23,34
probe 01	15,7	15,66	16,20			19,29
probe 02	15,56	15,64	16,68			19,42
probe 10	14,49	17,88	20,51			19,52
probe 11	16,02	15,69	15,95			17,72
probe 12	15,56	20,52	23,98			30,04
probe 14	12,47	14,92	17,42			17,85

Figure 26 : Evolution of the temperatures measured as a function of charging time. Tests with the UGE dry granular material

The maximum temperature evolution was obtained with the probe n°12, placed just above the Litz wires. At this point, the temperature increase was 15 °C after 5 hours of charging.

Similar tests were also performed with the wet granular material, with a percentage of water of 3 %. The results indicated no change of behaviour in the presence of water.

5.6.3 Mechanical performance tests

The mechanical behaviour of the solution proposed for the integration of the coils in the pavement, under was evaluated as follows :

- First, several candidate materials were selected for the insulating block containing the coils, and for the resin , used as joint between the coil and the bituminous concrete.
- Then, wheel tracking tests (simulating loading by a moving wheel) were performed on slabs of asphalt material, in which a block, simulating the coil, was integrated, to evaluate the resistance of the embedded coils to traffic loading.
- In addition, four point bending tests were also performed, to evaluate the strength of the interface between the different resins and the coil blocks.

The candidate materials selected for the laboratory testing were :

- For the coil block : A high density polyethylene (PEHD), A polyamide (PA),with properties similar to the PEHD, and two polyurethane resins, proposed by CEFEM, which will manufacture the final coil prototypes, one rigid polyurethane (PUR) with a high elastic modulus and a semi-rigid polyurethane (PUSR), with a lower elastic modulus.
- For the resin : two resins used for sealing of rails in asphalt pavements, VA60 (very deformable) and M95 (with a higher stiffness) and a product used for sealing pavements cracks (Plastiroc).

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These materials were selected for their adequate mechanical and insulating properties, and resistance to temperatures of asphalt layers (160 °C). Details on these materials are given in deliverable D 4.10.

5.6.3.1 Wheel tracking tests

The wheel tracking test (or rutting test) is designed to evaluate the resistance to rutting of asphalt materials at laboratory scale. The test procedure is defined by standard EN 12697-22. The test consists of subjecting an asphalt slab to repeated loading, using a wheel with a rubber tire, which rolls back and forth on the surface of the slab, under stress conditions close to those generated by heavy vehicles. The rutting test is performed using the LPC wheel tracking device (Figure 27). The test conditions are the following : specimen dimensions 500*180*100 mm; Applied load: 500 daN; loading frequency 1 Hz; test temperature 60 °C.

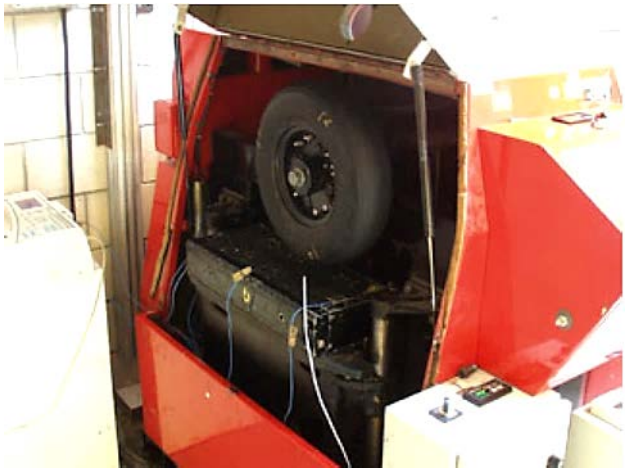

Fig. 27: LPC wheel tracking apparatus

For the evaluation of the VEDECOM solution, laboratory prototypes with the coil block and resin integrated into the pavement slab were prepared. The slabs were composed of a 7 cm layer of dense bituminous concrete (Béton Bitumineux Semi-Grenu – BBSG) in which a block, simulating the primary coil was inserted and sealed with resin . This base was then overlaid with a 3 cm-thick layer of Very Thin Bituminous Concrete (Béton Bitumineux Très mince – BBTM). The geometry of the tested specimens is shown on figure 28.

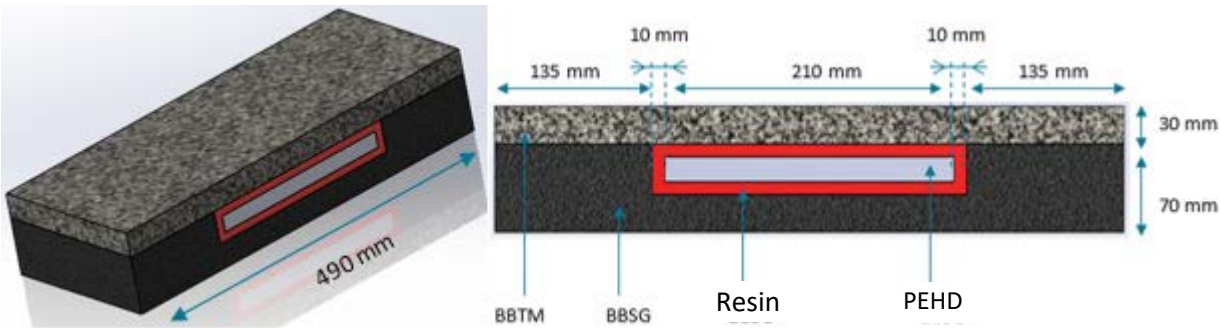

Fig. 28: Geometry of the wheel tracking test specimen.

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To evaluate the resistance to wheel loading of the embedded VEDECOM coils, rutting tests were successively performed on 8 samples :

- Samples 1and 2 were made with the PEHD coil block an soft VA 60 resin. Tests on these two samples indicated very high (inacceptable) levels of rutting, largely exceeding 10 mm after 30 000 cycles (maximum allowed limit)
- Sample 3 consisted only of the two asphalt layers, without coil block, and sample 4 was made again with a PEHD block and VA60 resin. Here, the tests indicated a good level of rutting of sample 3 (6,5 % after 30000 cycles), whereas sample 4 presented again a very large rutting. This result led to conclude that the large rutting was caused by the soft VA60 resin, and not by the quality of the asphalt materials.
- Then, tests were performed on samples 5 and 6, made with a PA coil block, and with the two other resins, M95 and Plastiroc. These two tests led to good rutting performance, with rutting levels of 5.38 % and 3.97 % respectively, after 30 000 cycles.
- Two last test, 7 and 8, were performed with the semi-rigid polyurethane (PUSR) for the coil block, and again the Plastiroc and M95 resins. These tests led again to good results, with rut depths of 4.97 and 7.27 % respectively after 30000 cycles, with a slight advantage for the Plastiroc resin.

From all the rutting tests, it could be concluded that :

- the resin VA 60 did not perform well, due to its insufficient stiffness, causing significant rutting.
- The stiffer resins, Plastiroc and M95, led to satisfactory levels of rutting (less than 10 %) with the two materials used for the coil block (PA and PUSR); However, final investigations made after the tests indicated that sample n°8 with the M95 resin presented some debonding at the interface with the asphalt layer. Therefore, the Plastiroc resin appeared as the most suitable for sealing the coil blocks.

5.6.3.2 Four point bending tests

In addition to the wheel tracking tests, four point bending tests were carried out to estimate the strength of the bond between the resins and the materials proposed for the coil block. The four point bending test consists in applying a load distributed on two loading points, on a beam supported at 2 points at its ends. The tests were conducted in controlled displacement mode (1 mm/min). To test the resistance of the interface between the coil block and resin, each beam was made of 3 parts : 2 bars of 50 mm X 20 mm section and 80 mm length, made with the coil block material, separated by a 20 mm thick layer of the tested resin. Figure 29 presents the test set up.

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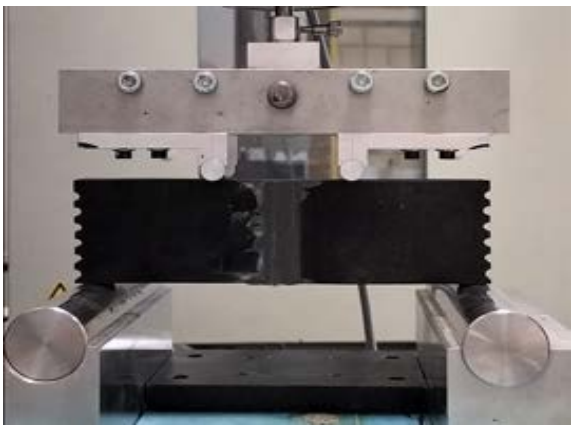

Fig. 29: Test set-up for the four point bending tests

A total of 8 four point bending tests were performed, with:

- two materials for the coil box: The rigid polyurethane (PUR) and the semi-rigid polyurethane (PUSR);
- Two resins: Plastiroc and M95;
- Two surface conditions between the resin and the box: smooth and rough.

The test results led to the following conclusions :

- The values of maximum tensile stress(at failure) obtained in all the tests were higher than tensile stress levels produced in asphalt layers by standard traffic loading (around 1 MPa maximum). Therefore, for all the tested conditions, the resin/coil box adhesion was found to be satisfactory.
- However, the tests indicated a higher interface resistance with the PUR material (for both resins), and also a much lower deformability of the PUR material.

From these results, it was concluded that the best material for the coil block is the rigid polyurethane (PUR), whereas the two resins lead to similar bond strengths.

5.6.3.3 General conclusions of the mechanical tests

Two types of tests were performed, to evaluate the mechanical performance of the coils embedded in pavement materials :

- Wheel tracking tests, simulating the effect of traffic loads on the embedded coils. These tests led to select the Plastiroc resin, as most suitable for sealing the coil blocks in the asphalt layer.
- Four point bending tests, used to estimate the bonding strength between the resins and the coil block materials. These tests were performed with two resins, Plastiroc and M95, and two coil block materials: rigid polyurethane (PUR) and semi rigid polyurethane (PUSR). The results indicated good bonding properties in all cases, but a low modulus of the PUSR material (only about 50 MPa), making the PUR more suitable for the coil block

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5.7 Laboratory tests with the CIRCE system

5.7.1 Testing of charging performance and temperature variations

For the CIRCE system, the design was not finalised at the end of task 4, and in particular the Litz cable for the coils had not been selected yet. Thus, it was not possible to perform the same type of charging tests and mechanical tests as for the Vedecom system. For this reason, some preliminary charging tests were performed on the Vedecom test bench, using the Vedecom coil prototypes, with the materials (aggregates and asphalt) proposed by Eurovia for the project, only to verify the suitability of the proposed materials.

The tests were performed using the same test procedures as described in § 5.6, including :

- Tests of charging efficiency and thermal behaviour with 2 types of 0/10 mm granular materials , from Chailloué quarry (quartzite) and from Luché quarry (Quartz, Cristobalite-tridymite). These two materials were tested dry, and a test with the Chailloué aggergates (proposed for the construction of the demonstrator) was also performed with wet aggregates.
- Tests of charging performance and thermal behaviour with two different asphalt concretes (BBSG 0/10 mm), made again with the Chailloué aggregates.

5.7.1.1 Tests with granular materials

The test procedure, similar to that described in § 5.6.2, consisted in embedding the primary coil in the granular material, compacted in a plastic container, and placing above the secondary coil (5 cm above the surface of the granular material) and then performing charging tests. Six temperature probes were placed in the container, to monitor temperature variations after different periods of charging

The tests consisted in applying cycles of 3 minutes of charging / 3 minutes of shutdown, during 2 hours, with a power supply of 15 kW, and measuring the charging efficiency and the temperature variations.

Two test were performed with this setup, with the Chailloué and Luché aggregates in dry condition. A third test was performed with wet Chailloué aggregates, and addition of de-icing salt, in order to simulate winter de-icing. In this third test, a solution saturated with de-icing salt was mixed with the aggregates, to obtain a water content of 5 %.

The charging efficiency measurements, with the different aggregates, led to values of charging efficiency varying between 86.7 % and 91.1 %, very similar to those obtained with the UGE aggregates. No loss of efficiency was observed in presence of water and de-icing salt. The temperature variations during charging were also measured, and again, very similar results were obtained as with the UGE aggregates, indicating no significant difference of results with the different types of aggregates.

5.7.1.2 Test with asphalt materials

Two charging tests were performed with two asphalt materials, proposed by Eurovia. These materials are both 0/10 mm wearing course materials (BBSG 0/10), made with the same aggregates (Chailloué), and with two different bitumens : a pure bitumen of penetration grade 35/50, and a modified bitumen (Styrelf) of penetration grade 13/40. As in § 5.6.1, the tests were performed with 400 mm x 600mm x 60 mm thick plates of asphalt materials, interposed between the primary and secondary coils.

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The charging procedure was the same as in the tests with aggregates (2 hours of charging, with 15 kW power, with 3 minutes long charging cycles and rest periods). The results of the tests indicated a good charging efficiency (90.7 % and 90.3 %) with the two materials, similar to that obtained previously with the UGE materials, and only very limited temperature elevations (3.5 °C) during the tests. However, the small temperature increase was due to the test set-up, where the asphalt plates were interposed between the primary and secondary coils.

5.8 Thermal modelling of the charging systems

In parallel with the laboratory tests, modelling has been carried out, to model the thermal response of the bituminous pavement structure with the embedded primary coils. The simulations consisted in performing finite element calculations, in 2D, with a model simulating the coil embedded in the pavement, and studying the thermal response of the pavement, due to the heat generated by energy losses in the embeded primary coil. The simulations were performed both for the Vedecom and CIRCE charging systems.

5.8.1 Thermal modelling of the Vedecom system

Simulations have been performed, first with the VEDECOM coil, embedded in a bituminous pavement structure. A charging power of the coils of 30 kW, and an energy loss (dissipation by Joule effect) of 4 % in the primary coil, embedded in the pavement, were assumed. The simulations were performed with :

- Different charging durations (1, 3 and 12 hours)
- Two initial pavement temperatures (15 °c and 40 °C)
- Different boundary conditions (convective exchange with air at the surface of the pavement).

Figure 30 presents an example of finite element model used for the simulation of the VEDECOM system, implemented in a road structure. The model represents the litz wires, encased in a polyethylene block (In yellow on the figure), and sealed in the bituminous pavement with resin (in red on the figure). To simulate the heat loss in the litz wires, a heat flux of 350 W/meter was applied on the boundaries of the wires. This heat flow was applied continuously during 1, 3 or 12 hours. This corresponds to “worst case” conditions, because in reality the charging will be intermittent, depending on the vehicle traffic.

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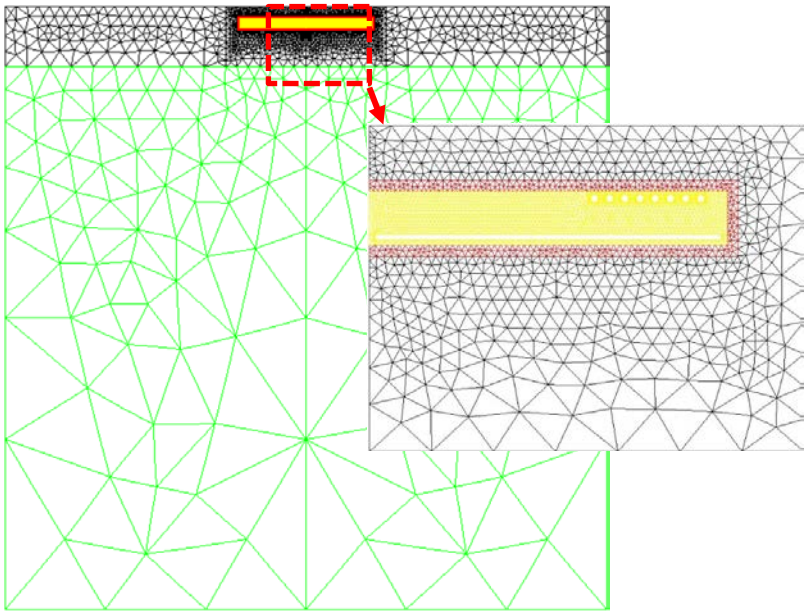

Figure 30: 2D mesh of the finite element model of the VEDECOM coil, integrated in a bituminous pavement.

First simulations were performed with an ambient (air) temperature of 15 °C, and 3 charging times : 1, 3 and 12 hours. Only the results of the simulation with a charging time of 12 hours are presented here. Examples of temperature fields obtained with a continuous heat flow of 350 W/meter during 12h are presented in Figure 31. The results indicate that :

- After 1 hour of heat flow, the maximum temperature inside the coil block reaches about 60 °C, and the temperature at the interface with the asphalt concrete (AC) is about 30 °C
- After 6 hours of heat flow, the maximum temperature inside the col block is about 120 °C, and about 50 °C at the interface with the asphalt concrete
- After 12 hours the maximum temperature inside the coil block reaches 140 °C; and about 60 °C at the interface with the asphalt concrete.

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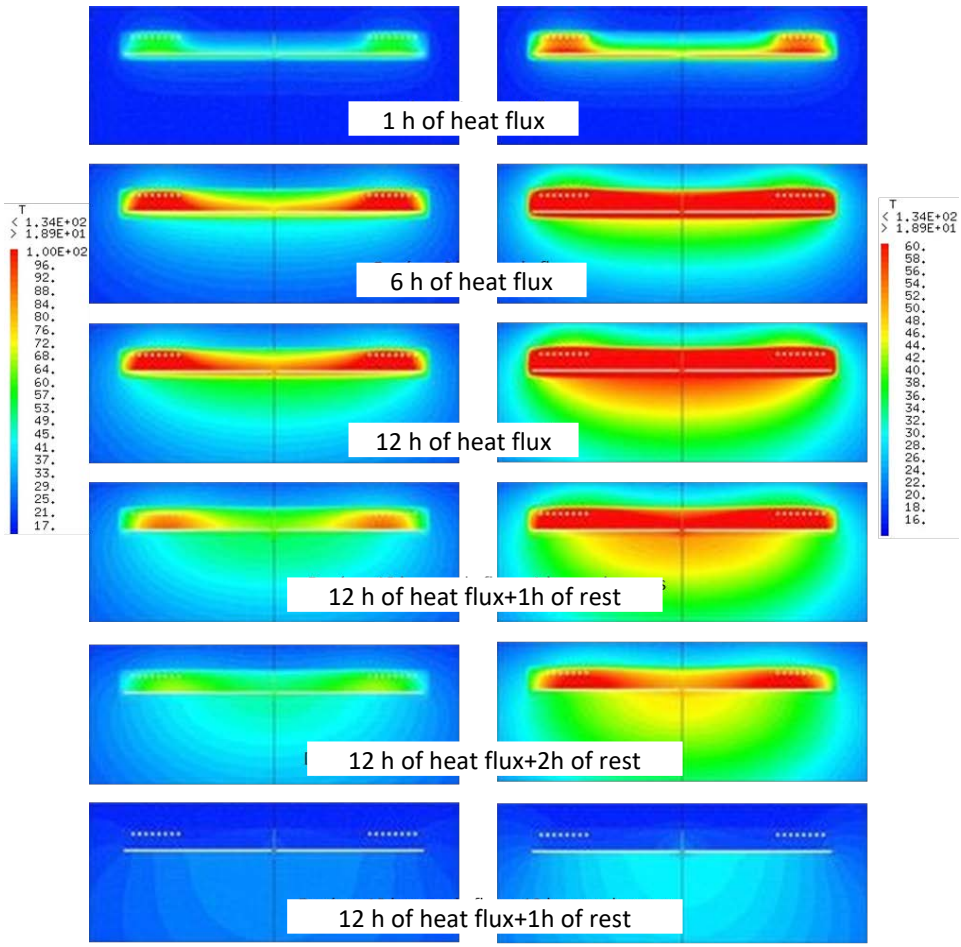

Figure 31: Temperature fields due to 12h of heat flow (ambient temperature 15 °C)
On the left, temperature scale from 15°C to 100°C. On the right, temperature scale from 15°C to 60°C.

Figure 32 summarizes the evolution of the maximum temperature reached inside the coil block and inside the AC specifically. The results show that after 12 hours the temperature inside the coil block, can reach high values (about 140 °C) in the worst case considered here, i.e. 12 hours of continuous operation. This means that this risk of high temperatures needs to be taken into account in the final design of the coil block, and choice of materials. In the same case, the maximum temperature in the asphalt concrete can reach 60 °C, which is approximately the maximum service temperature for standard asphalt materials.

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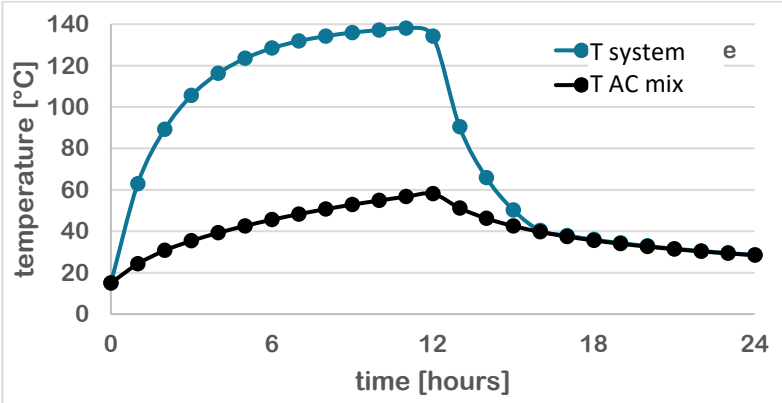

Figure 32. Evolution of the maximum temperatures in the e-road (in the coil block and in the AC) for 12 hours of continuous charging time (ambient temperature 15 °C)

Similar simulations were performed with an ambient (air) temperature of 40 °C, and again 3 charging times : 1, 6 and 12 hours. Again, only results with 12 hours of charging time are presented here . Figure 33 shows the evolution of the maximum temperatures reached inside the coil block and inside the AC layers. Here, the temperature inside the Polyethylene box, between the wires and the ferrite, can reach 157°C for a continuous operation during 12 hours. In the asphalt concrete, the maximum temperature can reach 68 °C after 12 hours of operation.

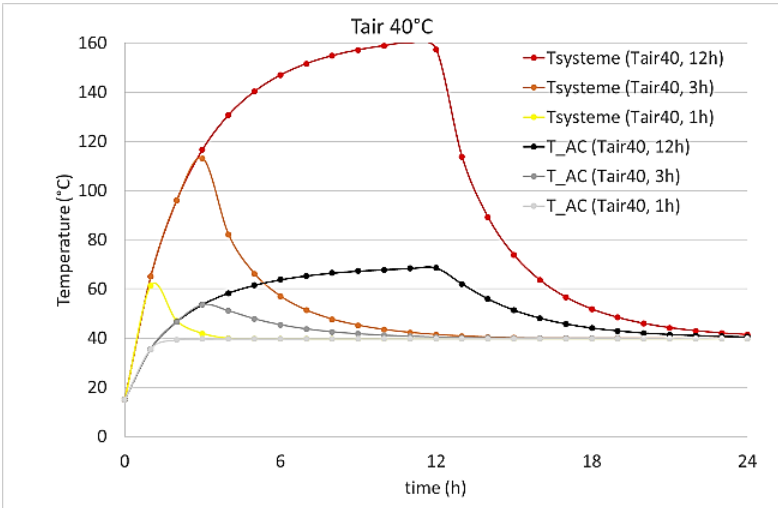

Figure 33. Evolution of the maximum temperatures in the e-road (in the coil block and in the AC) for 12 hours of continuous charging time (ambient temperature 40 °C)

In conclusion, these thermal simulations, performed for “worst case conditions” indicate that :

- Because the coil block and resin act as insulators, high temperatures can be attained inside the coil block, close to the litz wires. In the asphalt layer, which has a high thermal inertia, the simulations indicate temperatures which remain below 60 °C, even after 12 hours of continuous charging, with

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an ambient temperature of 15°C . In hot summer conditions (ambient temperature 40 °C) , the temperature could attain higher values (68 °C after 12 hours) in the asphalt layer.

- These first results will have to be validated in a full scale experiment, but indicate that the primary coil system needs to be designed to resist to high temperatures.
- For the asphalt materials, risk of exceeding the limit service temperature (about 60 °C) exists only in hot summer conditions (ambient temperature of about 40 °C). This risk can be limited by the choice of specific asphalt mixes, with a high rutting resistance.

5.8.2 Thermal modelling of the CIRCE system

The same approach has also been used to perform thermal simulations for the CIRCE system. As previously, a finite element model of thermal diffusion with time is considered. The calculation is made in 2D, on a transversal section of the road. The CIRCE system is represented by a single Litz cable coil, protected by a polyethylene covering. This coil is integrated in the base course and sealed with resin. The subgrade consists of a standard unbound granular material (as for the Vedecom system). A condition of convection is applied at the surface of the road to simulate the heat exchanges with air. Figure 34 presents the mesh of the model

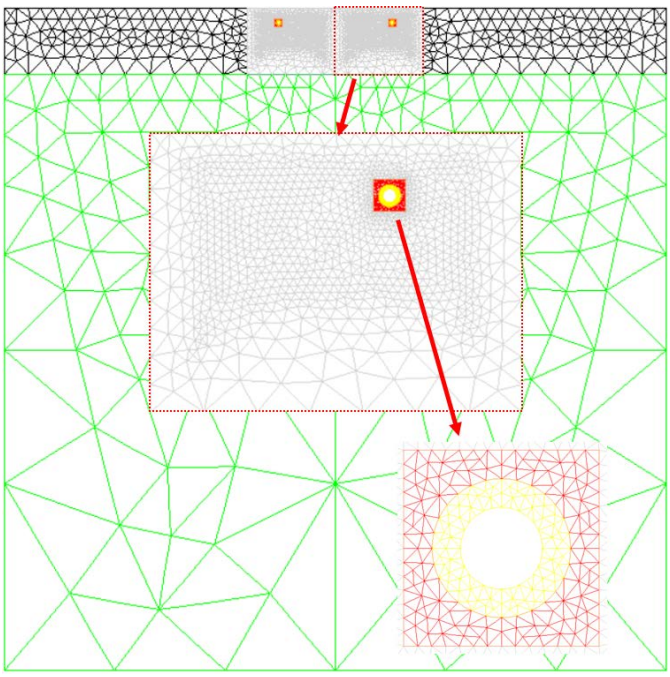

Figure 34 Mesh used for the thermal diffusion computations with the CIRCE system.

To simulate the heat loss in the cable, a heat flow of 180W / meter was applied on the boundary of the cable. As for the Vedecom system, simulations were performed with3 charging durations (1, 3 and 12 hours) and two initial pavement temperatures (15 °c and 40 °C).

The results of the simulations with the CIRCE system are summarised on Figure 35, which shows the evolution of maximum temperatures inside the system and in the asphalt concrete with charging time.

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Simulations performed at T air=15°C show that the system (polyethylene + resin) reaches quickly 140°C after 3 hours of heat flow, and then stabilizes around 160°C. In the asphalt concrete, the temperature never exceeds 60°C, considered as a "critical" service temperature.

Simulations performed at Tair=40°C show that the system (polyethylene + glue) reaches quickly 150°C after 3 hours of heat flow. Then the temperature continues to increase, but much more slowly, and reaches 175°C after 12 hours of heat flow. In the asphalt concrete, the maximum temperature reaches a relatively stable value of about 70°C. This temperature exceeds the critical service temperature (60 °C), but only in a small zone around the Litz wire.

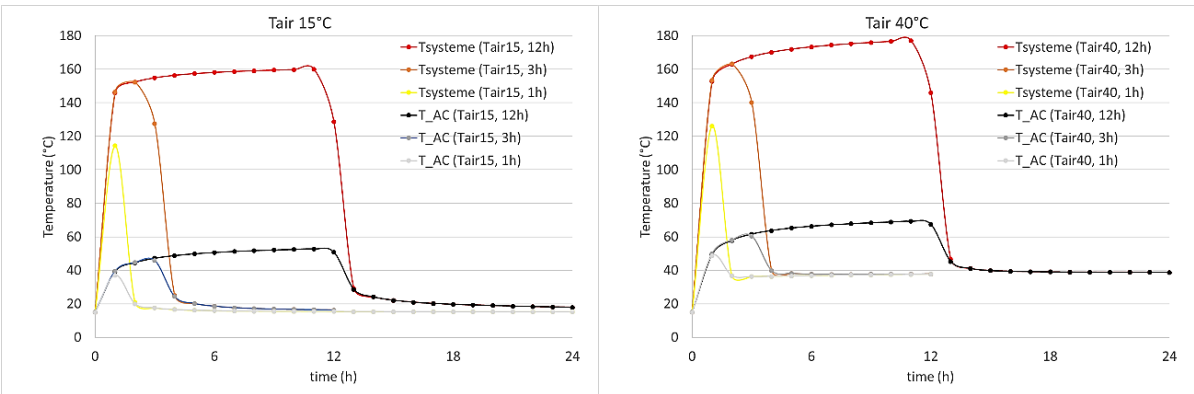

Figure 35: Maximum temperatures reached inside the Circe system (on the left) and in the asphalt concrete (on the right) for the two values of air temperature Tair = 15°C and Tair = 40°C.

The results with the CIRCE system are relatively similar to those with the Vedecom system and indicate that, for the "worst case" conditions used for the simualtions (40 °C ambient temperature, 12 ,hpurs of charging):

- Temperatures attained inside the primary coils can potentially be very high for both systems (above 160 °C after 12 hours of continuous charging).
- Maximum temperatures in the asphalt after 12 hours of charging can reach 68 °C to 70 °C

5.9 Modelling of the mechanical response of the charging systems under traffic loading

Finally, finite element calculations were performed to evaluate the mechanical response of the charging systems under traffic loading. These calculations were performed only for the Vedecom system (which design is finalized). The calculations were performed with the Solidworks software, in 3D and under static loading, considering a linear elastic pavement model. The considered load was the standard axle load used in France for pavement design, which is a dual wheel axle, with a load of 130 kN [3]. The temperature and frequency conditions used for these calculations (15 °C, 10 Hz) were also those used in the French pavement design method.

The pavement structure considered for the calculations is shown on figure 36. It consisted of a 25 cm-thick bituminous structure, resting on a subgrade with a modulus of 50 MPa. The coil block was inserted in the upper part of the base course (sealed with resin), and covered with a 5 cm thick surface course.

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Fig. 36: Model of the pavement structure with the embedded Vedecom charging system (transversal profile)

The calculations were performed with standard material properties of French bituminous materials, and considering the rigid polyurethane for the coil block. For the resin, two cases were considered: the soft VA60 resin (modulus 50 MPa) and to the much stiffer Plastiroc resin (modulus 5660 MPa). The calculations were also performed for 6 different positions of the dual wheels relative to the embedded coils :

- Case 1 : coils located under the centre of the axle.
- Case 2 : left wheels located just at the edge of the coils.
- Case 3 : left wheels centred on the coils. This is the situation where the coils are submitted to the highest vertical stresses.
- Cases 4 to 6 : the same 3 transversal positions, but with the wheels placed longitudinally at the joint between two coils.

These 6 wheel positions are illustrated on figure 37.

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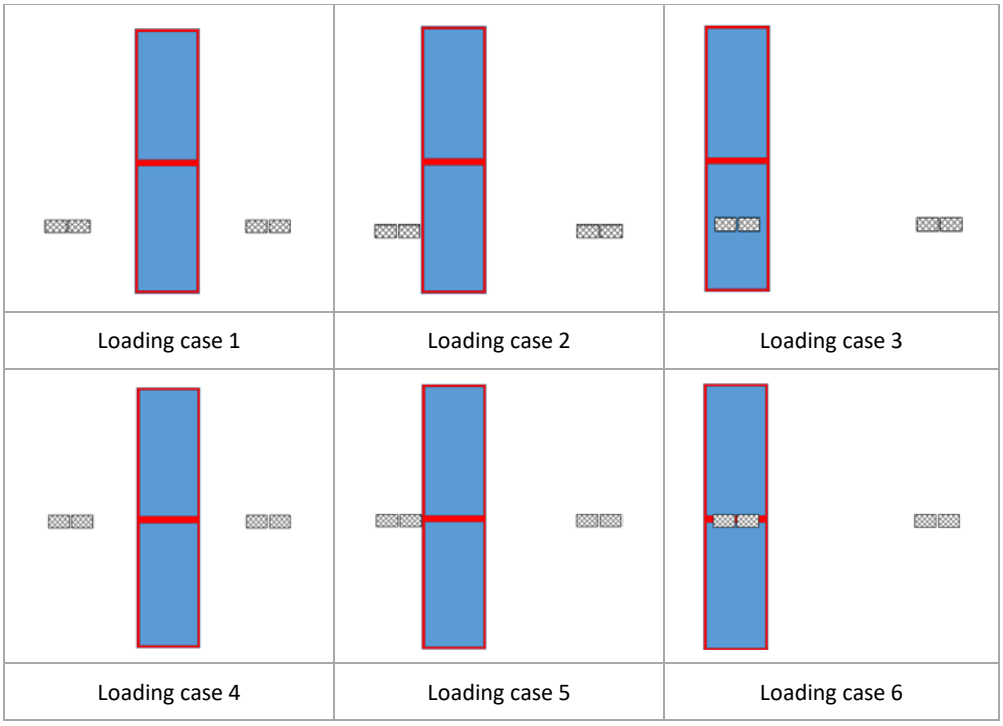

Fig. 37: Summary of the 6 loading cases (positions of the wheels relative to the coils).

To validate the response of the pavement under heavy vehicle wheel loading, 3 main criteria were used :

- The maximum positive (tensile) principal stress σ_1 in the asphalt layers (criterion relative to the tensile strength of the asphalt layers).
- The maximum positive (extension) principal strain ε_1 (criterion used for fatigue of asphalt layers)
- The maximum vertical strain in the subgrade εz (criterion used for rutting of the subgrade).

As mentioned, the calculations were performed considering two different sealing resins : the Edilon Sedra VA 60 resin and the Plastiroc resin, which presented the best performance in the laboratory tests. The modelling results cannot be presented here in detail, but they indicated a strong influence of the choice of the resin on the mechanical response of the pavement.

With the VA 60 resin, results indicated :

- An acceptable response of the pavement structure when the coils are in the middle of the axle, at a sufficient distance from the wheels. This is the “normal” loading situation, when the vehicles drive in the middle of the road lane.
- High, unacceptable, tensile stresses and strains when the vehicle wheels pass at the edge of the coils, or over the coils. Note that this situation will occur only when the lateral position of the vehicles changes (when they turn or change lanes).

With the Plastiroc resin, the stresses and strains in the pavement structure remained acceptable whatever the position of the loads. This can be explained by the small contrast between the modulus of the resin, of the coil block and of the asphalt layers. These calculations confirmed the results already obtained in the laboratory mechanical tests, which indicated that the Plastiroc resin is a good candidate for sealing the coils in the pavement.

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5.10 Conclusions of task 4.4

After a review of different existing WPT systems, and in particular of solutions for integrating these systems in roads , the objective of task 4.4 was to propose and validate solutions for integrating the charging systems developed in the INCIT-EV project in bituminous road structures. For that purpose, a specific approach, based on laboratory tests, and pavement modelling was proposed.

After selection of appropriate materials for the protection of the coils and for the pavement structure, this approach consisted in performing :

- **Charging tests**, to evaluate the charging performance of the coils embedded in pavement materials. These tests have been performed using a dedicated test bench, developed by Vedecom
- **Thermal behaviour tests**. These test consisted in simulating different charging conditions, with the coils embedded in granular materials, and measuring the temperature increases produced by the energy losses by Joule effect, when the coils are in operation
- **Mechanical tests** on the materials proposed for the coil block and for the resins used for sealing the blocks in the pavement. These included measurements of tensile strength, adhesion between materials and elastic modulus by four point bending tests
- **Wheel tracking tests,** used to simulate the effect of moving wheel loads on reduced scale specimens, simulating the coil blocks embedded in asphalt materials.
- **Thermal finite element simulations**, designed to simulate the thermal response of the primary coils embedded in an asphalt pavement
- **Mechanical finite element simulations**, designed to simulate the mechanical behaviour of the primary coils embedded in an asphalt pavement, under heavy traffic loads.

This methodology was applied to the two charging systems developed in the INCIT-EV project for dynamic inductive charging, for the Urban (UC2) and interurban (UC3) use cases. The main results obtained can be summarised as follows:

- The charging tests indicated no significant influence of the selected pavement materials on the performance of the charging systems both in dry and wet conditions
- The temperature measurements and thermal simulations allowed to estimate the heating due to the operation of the charging systems. They indicated that high temperatures (exceeding 100 °C) could be attained inside the charging elements in case of prolonged continuous charging. In the asphalt layers, temperatures could exceed 60 °C (and reach about 70 °C) in hot summer conditions. These results are only orders of magnitude, obtained for “worst case conditions”, but they indicate that it is necessary to pay attention to the temperature resistance of the materials, and to monitor temperatures in the demonstrator to avoid excessive temperatures and turn-off the system if necessary in case of excessive heating.
- Mechanical performance tests were performed only for the Vedecom charging system, and helped to select suitable materials for the coil block, and the resin used to seal the coil blocks in the asphalt layers. The wheel tracking tests indicated that a low modulus of the coil block, or of the resin, lead to risks of rutting and failure of the asphalt layers, and that a modulus of the same order of magnitude as the asphalt materials leads to satisfactory performance. The 4 point bending tests allowed in particular to verify the good bonding between the resin and the coil element. The study led to select **the PUR material for the coil block, and Plastiroc for the resin**.

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- Mechanical modelling contributed to evaluating risks of deterioration of the charging system under traffic loading, They indicated that high stresses and strains are generated around the embedded charging system only when the vehicle wheels pass above the coils, or close to their edge. This means that the charging systems will not be submitted to high stresses or strains when the vehicles drive in the middle of their lane, but only when the vehicles change their lateral position (when they turn or change lanes). In addition, the simulations indicated risks of high stresses and strains only with the low modulus resin (VA 60). Stresses and strains remained acceptable in the whole structure with the stiffer resin (Plastiroc), thus confirming the choice of the Plastiroc resin for sealing the coils in the pavement.

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6 TASK 4.5 - DEVELOPMENT OF THEFT-PROOF PARKING AND CHARGING SYSTEM FOR ELECTRIC 2-WHEELERS

6.1 Task Objectives

This section concerns task 4.5 , which is carried out by IDNEO. On the basis of experience acquired with previous systems, IDNEO was in charge of developing a new, innovative parking system for two-wheelers (bikes and kick-scooters, combining secure parking and charging functions. The objectives were :

- To develop a system which is more compact than current theft-proof systems, to minimize visual impact and facilitate installation
- To propose a wireless battery charger, compatible with a large variety of electric two-wheelers (interoperable), which can be used both for commercial vehicle fleets and for private use
- To provide an efficient locking system, to prevent theft, which is a major concern for these vehicles.
- To propose a solution which is easy to use, and of reasonable cost.

Over the last years, electric 2-wheelers have changed mobility in most large European cities with an important role in the reduction of NOx and CO_2 emissions. Electric bicycles and scooters, both in private and shared use, represent a very interesting alternative to other vehicles in urban areas, especially in combination with public transport. The interoperability between the different types of 2-wheelers and public transport, and the facility for parking and charging these vehicles represent key factors in the success of these alternative mobility systems.

To develop this new parking and charging system, a state of the art review of charging and anti-theft solutions for 2 wheelers has first been carried out. After this review, the main characteristics of the new parking system have been defined, and will be presented in this section.

6.2 Review of existing parking and charging solutions for two-wheelers

6.2.1 Electric bike-sharing systems

The use of electric bikes and electric scooters has increased considerably over the last few years in the EU. In 2019, the number of e-bikes sold was close to 3 million, and the use of kick scooters is also increasingly popular, with more than 125 cities in Europe using these types of vehicles in sharing systems [13].

In many of these cities, the increase of robberies and vandalism of these 2-wheelers systems, either public for sharing use or for private use is a major concern. Novel anti-theft solutions combined with flexible and safe battery charging solutions are required by all the stakeholders: end users, fleet operators and municipalities.

A review of European bike-sharing systems [14] indicated that the following cities in Europe have the most important systems, with the following daily uses of each bicycle :

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- **Barcelona** (10.8 trips per bike, 67.9 trips per 1,000 inhabitants)
- **Lyon** (8.3 trips per bike, 55.1 trips per 1,000 population)
- **Paris** (6.7 trips by bike, 38.4 trips per 1,000 inhabitants

The study also indicated that the following criteria are important for a good bicycle sharing system :

- Having multiple stations well located within no more than approximately a 325-meter radius.
- Have multiple bicycles available (10-30 per 1,000 populations in the coverage area)
- A coverage area of more than 10 square km
- Solid bikes with hardware that discourages theft
- Easy to use payment systems and stations.

A very important points to take into account for electric 2 wheelers sharing systems, is the control of the battery charge cycle : how to ensure that users do not run out of battery power in the middle of a journey and how to charge the battery rapidly and safely, with minimum impact on the availability of the bikes.

However, the major concerns with these new mobility systems are risks of theft and vandalism. In the case of bikes for sharing use, two major types of locking technology are employed :

- Bikes lock to a rack or kiosk where users collect and drop bikes by means of a magnetic card (see figure 38) . These systems are generally simple to operate, making them accessible to the general public. This type of system is called dock based system. These systems present a better protection against theft, and also allow to combine parking with charging, but require to install dedicated dock stations. Such systems are often used for bikes.

Figure 38. Dock-based bike station in the city of Madrid

- Bikes are secured using an electronic lock mounted on the bike. Users must use a mobile phone to unlock the bike via a code received from the operator company. This type of system is known as Free-floating system or dockless. This system presents a better flexibility, because the vehicles can be parked anywhere, without the need to install dock stations; the vehicles are then located using their integrated GPS, which requires a smartphone application. However, because the vehicles are

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not attached to a fixed rack, there is a greater risk of theft or vandalism. Free floating systems are predominantly used for kick scooters.

In INCIT-EV, the objective is to combine parking and charging, and therefore the solution that will be studied is a dock-based system. For such systems, there are two main types of locking systems, depending on the part of the bicycle which is attached :

Fork lock systems :

Fork lock blocking is the most common and secure method found in docking based systems. This system can be used either with electric or mechanical bikes. In case of electric bikes, battery charger connections can be included in the blocking mechanism, to ensure protection of the power terminals (Figure 39).

Figure 39. Fork lock dock station of Madrid electric bike sharing system

Hub lock system :

Front hub blocking systems can be used as well in docking based systems for electric and mechanical bikes. In this case, battery charging terminals are more exposed to external disturbance than in the case of fork locks systems.

In INCIT-EV, as the objective is to propose a parking and charging system which can be used for both bicycles and kick-scooters, the fork lock system seems the most suitable.

6.2.2 Reference electric bike sharing solutions of European cities

To define the characteristics of the new parking and charging system, different existing systems from major European cities and sharing services companies have been studied. A detailed analysis of these different solutions can be found in the deliverable D4.5 “Report on theft-proof parking and charging systems for two-wheelers” of INCIT-EV. The following systems have been reviewed :

- ***Bicing,*** the bike sharing service of the city of Barcelona [15].
- ***Bicimad,*** the public electric bicycle service of Madrid [16]
- The systems developped by ***Smoove,*** a French company which develops bike sharing systems implemented in 22 cities [17]

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- The systems developped by **PBSC**, a Canadian company, also developing bike sharing systems for several large cities [18].

Most of the analysed systems are made only for bicycles (classical or electric), and use fork lock blocking systems. The lock also includes the connector for electric charging.

Recently, PBSC unveiled a more innovative solution, which also allows most types of kick scooters to dock and recharge at their smart stations**.** PBSC uses a triangular device to lock and charge the electric bikes. This system can also be directly mounted onto the frame of kick scooters, making these vehicles compatible with their docking points. It is thus the first charging and parking solution compatible with different 2-wheelers.

6.3 Innovative charging and parking system for two-wheelers developed by IDNEO

On the basis of previous experience and of the review of existing systems, IDNEO has defined several innovative characteristics for the new charging and parking system to develop in INCIT-EV :

- The locking system will be interoperable, compatible with both bicycles and kick-scooters.
- The vehicles will be equipped with connectors for charging the battery, compatible with any kind of vehicle.
- The charging will be wireless, thus eliminating plugs, and reducing the risks of vandalism and reducing maintenance.
- The dock stations will be compact and adaptable, to allow installation in different strategic locations of the cities (kiosks, poles, walls, …).

The main characteristics of the system are detailed below. A view of the charging station is shown on figure 40.

Figure40. INCIT-EV User Case Electric 2-wheeler and Charge Station

The electrical architecture of the system is based on a high-voltage 700 V DC bus generated from a rectifier placed in the user centric station that allows the connection of both high-power bidirectional EV chargers and low-power 2-wheeler chargers.

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A dedicated 700 V DC to 24 VDC Buck Converter is integrated in each low power charger station to supply energy to the lockers, controllers, and full bridge inverters (see figure 41). Energy is transferred by induction to the 2-wheeler, rectified again and afterward a dedicated buck – boost converter with special functions to be used as Battery Charger manages the cut off voltage and taper current of each battery pack.

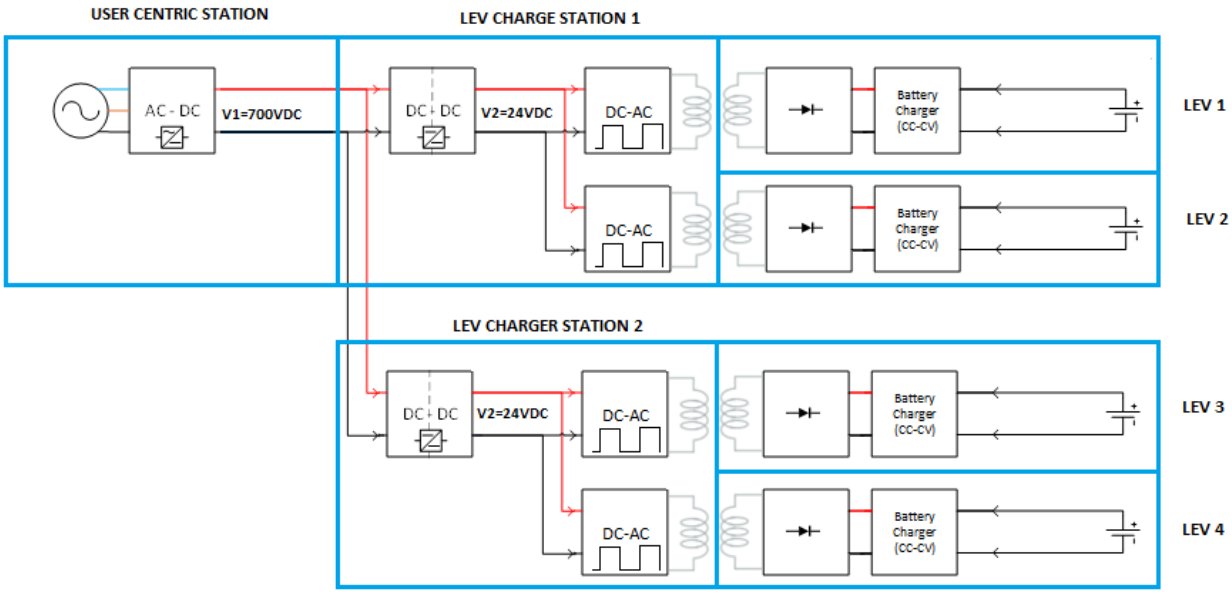

Figure 41. INCIT-EV Low Power 2 Wheeler charging System for Use Case 6

The anti-theft system is based in an individual charge station locker (figure 42) developed focusing in two main pillars: the lateral locking mechanism prevents manipulation of the 2 wheeler once it has been inserted into the station and the controller inside the locker prevents against any type of vandalism act, and on the other hand it is possible to modulate through the transferred energy a bidirectional communication protocol between the 2 wheeler and the backend of the charging station, securing the information exchanged that includes the unique identification of the vehicle in order to prevent fraud and misuse of the charging stations.

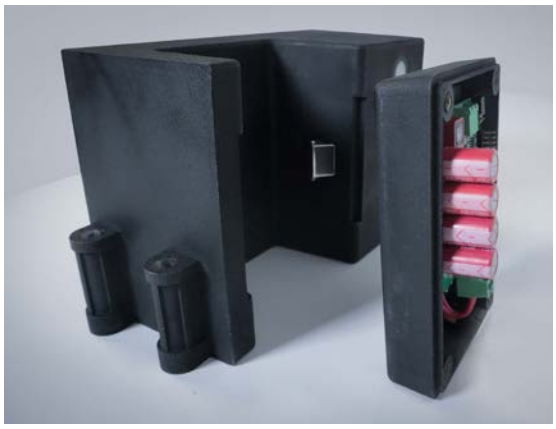

Figure42. Charge Station Locker

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The locking system has been developed in a way that can be used in any type of 2 wheeler: electric bicycle and kick scooter. Only a dedicated bracket for each type of vehicle target could be designed to adapt the anti-theft system for different models or brands of 2 wheelers

The charge station (figure 43) consists of a coil actuator, which is responsible for the active locking of the 2 wheelers to the station, position sensors and LED indicators, the Wireless transmitter (coil + inverter) and a controller for each charge point. These controllers have a unique identifier and connectivity possibilities with the backend through Wi-Fi using MQTT communication protocol.

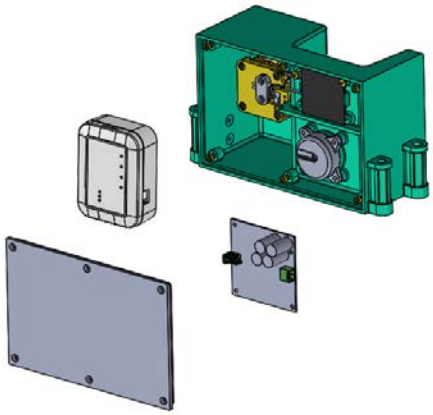

Figure 43. Elements of Charge Station Locker

6.4 Conclusion of task 4.5

The charging system for the 2-wheelers has been entirely designed, and is ready for implementation in the demonstrator for Use Case 6 at Zaragoza City. This charging system includes the following innovations :

- High Voltage DC Bus powered

The bidirectional electrical architecture based on a high voltage direct current bus (700 V) used in the 2-wheel charge station of Use Case 6 increases energy efficiency by reducing the number of rectifiers required, allows energy exchange with nearby building installations and the fast roll out of public 2-wheelers charge stations as well as their integration with renewable energies.

- Electromechanical anti-vandalism locking systems

New anti-theft locking systems developed including IoT technology to provide more intelligence and security to the dock station. Each of the dock stations has enough intelligence to communicate with the backend and to self-diagnose in case of failures or any other type of problem, like vandal acts or robberies.

- Interoperable dock stations for different types of 2 wheelers: bikes and kick scooters

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The system developed is an interoperable charging system that allows both electric bicycles and scooters to be used in the same charging station. The locking system is compatible for both types of vehicles, and a compatible connector for any kind of vehicle to allow the charge of their battery has been developed.

- Wireless battery charging to avoid mechanical connectors

Wireless charging systems allow charging without the use of a physical connector, thus avoiding vandalism problems and reducing maintenance.

- Active communication (bidirectional) between 2 wheeler and dock station without the need of 2G/3G and Tag readers

In addition, the wireless technology allows modulating bidirectional communication signals for the exchange of data between the 2 wheelers and the dock station.

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7 GENERAL CONCLUSIONS

The following results were achieved in Work Package 4, during the first year of the INCIT-EV project.

- In Task 4.1 "Grid requirements for charging system deployment", a theoretical analysis of potential impacts that a large deployment of electric vehicles could have on the electric grid was performed. Then, in a second stage, simulations were carried out to analyse the effective impacts that could be expected in the context of different EV use cases (urban, inter-urban, peri-urban and parking frameworks). Finally, different measures that could be used to mitigate these impacts were discussed and evaluated.
- In Task 4.2 "grid services enabled by charging infrastructure and ESS deployment" a review of different grid services which can be provided by the charging systems and electric vehicles has been performed. Both services provided by grid operators and V2X services have been studied. Then, using the same scenarios as in task 4.1, simulations have been performed to assess the expected impacts of these services on grid performance.
- In Task 4.3 "Connection with DC networks and integration with tram / metro energy lines", potential advantages of using DC networks for charging of electric vehicles have been discussed, and different possible architectures of such networks have been analysed. A particular focus was made on connection with tramway or railway DC energy lines. Simulations of connection of chargers with an electric substation of the Turin Tramway network has been performed, in connection with use case 4 of INCIT-EV.
- In Task 4.4 "Infrastructure upgrading for dynamic wireless charging", different existing dynamic wireless charging systems have been reviewed. On the basis of this review, solutions for the integration in pavements of the systems developed by Vedecom (for urban use) and by CIRCE (for inter-urban use) have been proposed. Finally, an experimental program, associating laboratory tests and modelling, has been carried out, to validate the proposed solutions. These tests allowed to evaluate the operating temperatures, the charging performance and the resistance to traffic of the primary coils installed in the pavement.
- In Task 4.5 "Theft-proof parking systems for two-wheelers", a review of existing parking and charging systems for 2-wheelers has first been performed. Based on this review, an innovative charging station, with wireless charging system, adaptable to both bicycles and kick-scooters has been designed, for implementation in Use Case 6, in the city of Zaragoza.

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